Structures and physical properties of V-based kagome metals CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$

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We report two new members of V-based kagome metals CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$. The most striking structural feature of CsV$_6$Sb$_6$ is the V kagome bilayers. For CsV$_8$Sb$_{12}$, there is an intergrowth of two-dimensional V kagome layers and one-dimensional V chains and the latter lead to the orthorhombic symmetry of this material. Further measurements indicate that these two materials exhibit metallic and Pauli paramagnetic behaviors. More importantly, different from CsV$_3$Sb$_5$, the charge density wave state and superconductivity do not emerge in CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ when temperature is above 2 K. Small magnetoresistance with saturation behavior and linear field dependence of Hall resistivity at high field and low temperature suggest that the carriers in both materials should be uncompensated with much different concentrations. The discovery of these two new V-based kagome metals sheds light on the exploration of correlated topological materials based on kagome lattice.

INTRODUCTION

Two-dimensional (2D) kagome lattice is a paradigm to study the effects of strongly geometrical frustration which could host many exotic magnetic ground states like quantum spin liquid state with fractionalized excitations [1, 2]. When introducing charge degrees of freedom, Janus-like kagome lattice exhibits nontrivial topological electronic structures with unusual features of Dirac nodal points, flat band and saddle point [3–6]. More importantly, the combination of magnetic correlation and band topology leads to the emergence of various of exotic correlated topological phenomena in metallic materials with kagome lattice (kagome metals), such as large anomalous Hall effect (AHE) [6, 7, 8], negative magnetism of flat band [9], large magnetic-field tunability [10] and the formation of Chern gap with edge state [11].

Very recently, the kagome metals with electron correlations other than magnetic one have been extended to the V-based materials AV$_3$Sb$_5$ (A = K, Rb and Cs) and they exhibit the coexistence of charge density wave (CDW) state and superconductivity with a non-zero $Z_2$ topological invariant [12, 13]. Such phenomena are closely related to the physics of van Hove filling in kagome lattice [17–19]. Moreover, the CDW state with three-dimensional (3D) $2\times 2\times 2$ superlattice [20, 21] shows some exotic behaviors. For instance, the CDW state may have a chirality which could result in large anomalous Hall conductivity without long-range ferromagnetism [22–25]. In addition, there is an intricate relationship between CDW state and superconductivity. For example, when the CDW transition is suppressed with pressure monotonically, the superconductivity shows an unusual multiple-dome feature with a significant enhancement [26, 27]. The roton pair density wave state has also been observed in the superconducting state [31].

In order to understand these diverse properties of V-based kagome metals further, not only the comprehensive studies on AV$_3$Sb$_5$ but also the exploration of novel V-based kagome materials is important. For many of magnetic kagome metals, a series of compounds with the key kagome layer exist, such as the binary $T_mX_n$ kagome metals ($T = $ Mn, Fe, Co; $X = $ Sn, Ge; $m : n = 3 : 1, 3 : 2, 1 : 1$) [6]. Systematic studies on these materials can provide some important clues to understand the effects of different local structural environment and strength of interlayer coupling on the properties of kagome layer. But such kind of homologous compounds is still scarce in V-based kagome materials. In this work, we report the discovery of V-based kagome metals CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$, two homologous compounds of CsV$_3$Sb$_5$. The characterization of physical properties of single crystals indicate that these compounds show metallic behaviors without CDW and superconducting transitions down to 2 K.

METHODS

Single crystals of CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ were grown using self-flux method. High-purity Cs (ingot), V (powder) and Sb (grain) were taken in a stoichiometric molar ratio of 1 : 6 : 30 for CsV$_6$Sb$_6$ and 1 : 8 : 50 for CsV$_8$Sb$_{12}$, respectively, and placed in a quartz tube with alumina crucible under partial argon atmosphere. The sealed quartz tubes for both materials were heated up to 1373 K for 12h and soaked there for another 24 h. After that, for CsV$_6$Sb$_6$, the temperature was rapidly cooled down to 1273 K with subsequently cooling down to 1163 K at 1.5 K/h, and then the temperature was held there for 70 h. For CsV$_8$Sb$_{12}$, the temperature was cooled down directly to 1123 K with the rate of 2 K/h. Finally, the ampoules were taken out of furnace and the single crystals were separated from the flux by a centrifuge. Shiny crystals with typical sizes of $1 \times 1 \times 0.02$ mm$^3$ (length×width×thickness) for CsV$_6$Sb$_6$ and $4 \times 1 \times 0.1$ mm$^3$ for CsV$_8$Sb$_{12}$ can be obtained. Both crystals are stable in air. In order to prevent the reac-
tion of Cs with air and water, all the preparation processes except the sealing and heat treatment procedures are carried out in an argon-filled glove box. The elemental analysis was performed using the energy-dispersive X-ray spectroscopy (EDX). XRD patterns were collected using a Bruker D8 X-ray diffractometer with Cu $K_{α}$ radiation ($λ = 1.5418$ Å) at room temperature. Single crystal XRD patterns at 300 K were collected using a Bruker D8 VENTURE PHOTO II diffractometer with multilayer mirror monochromatized Mo $K_{α}$ ($λ = 0.71073$ Å) radiation. Unit cell refinement and data merging were done with the SAINT program, and an absorption correction was applied using Multi-Scans. The structural solutions were obtained by intrinsic phasing methods using the program APEX3 [32], and the final refinement was completed with the SHELXL suite of programs [33]. Electrical transport measurements were carried out in a Quantum Design physical property measurement system (PPMS-14T). The field dependence of $ab$-plane longitudinal and transverse electrical resistivity were measured using a five-probe method and the current flows in the plane of the crystal. The magnetoresistance and Hall resistivity were obtained from symmetrizing and antisymmetrizing the longitudinal and transverse resistivity measured at the positive and negative fields, respectively. The $c$-axis resistivity was measured by attaching current and voltage wires on the opposite sides of the plate-like crystal. Magnetization measurements were performed in a Quantum Design magnetic property measurement system (MPMS3).

RESULTS AND DISCUSSION

As shown in Fig. 1(a), CsV$_3$Sb$_5$ has a layered structure with hexagonal symmetry (space group $P6/mm$, No. 191). The $a$- and $c$-axial lattice parameters are 5.5055 Å and 9.3287 Å [13]. It consists of Cs, Sb and V-Sb layer stacking along $c$ axis alternatively (Fig. 1(a)). For the Cs layer, Cs atoms form a perfect triangle lattice with the distance of Cs atoms $d_{Cs-Cs} = 5.5055$ Å (Fig. 2(a)). For the Sb layer, Sb atoms compose a honeycomb lattice with $d_{Sb-Sb} = 3.1786$ Å and Cs atoms locate at the centers of each hexagons (Fig. 2(a)). Because there are two Sb atoms in one unit cell, this layer is denoted by the Sb$_2$ layer. The key structural ingredient of CsV$_3$Sb$_5$ is the 2D undistorted V kagome lattice in the V-Sb layer and the distance of V atoms $d_{V-V} = 2.7528$ Å (Fig. 2(b)). The Sb atoms occupy at the centers of V hexagons with $d_{V-Sb} = 2.7528$ Å when Sb atoms in the Sb$_2$ layer locate below and above the centers of V triangles (Fig. 1(d)). This V-Sb layer can be denoted by V$_2$Sb layer due to three V and one Sb atoms in one unit cell. Because there are one Cs, two Sb$_2$ and one V$_2$Sb layers in each unit cell, the chemical formula of CsV$_3$Sb$_5$ can be expressed as CsV$_3$Sb$_5 = Cs + 2Sb_2 + V_2Sb$.

FIG. 1. Front view of structures of (a) CsV$_3$Sb$_5$, (b) CsV$_6$Sb$_8$, and (c) CsV$_8$Sb$_{12}$. The big green, small red and medium blue balls represent Cs, V, and Sb atoms. The black lines represent the unit cell edges. (d) - (f) Side view of V-Sb building blocks emphasized by dotted rectangles in (a) - (c).

FIG. 2. Top view of (a) Cs, Sb$_2$ layers and (b) V$_2$Sb layer of CsV$_3$Sb$_5$, (c) Cs, Sb$_2$ layers and (d) 2V$_2$Sb bilayer of CsV$_6$Sb$_{8}$. (e) Cs, Sb$_2$ layers, (f) V$_2$Sb layer, and (g) (V$_2$Sb)$_2$ layer of CsV$_8$Sb$_{12}$. The corresponding Cs-Cs, Sb-Sb, V-V, V-Sb atomic distances in each layer are shown below the figures.
For layered CsV₆Sb₆, it has a similar hexagonal structural symmetry to CsV₃Sb₅ (space group R3m, No. 166) with \( a = 5.5575(8) \) Å and \( c = 35.165(9) \) Å (Table 1). The structures of Cs layer and Sb₂ layer with Sb1 and Sb2 sites in CsV₆Sb₆ are also similar to those in CsV₃Sb₅ and the former has slightly larger \( d_{Cs-Cs} (= 5.5055 \) Å) and \( d_{Sb-Sb} (= 3.2086 \) Å) (Figs. 1(b) and 2(c)). Instead of the V₃Sb monolayers in CsV₃Sb₅, however, there are 2V₃Sb bilayers with V and Sb1 sites in CsV₆Sb₆ (Figs. 1(b) and 2(d)), similar to that in Fe₃Sb_{2A} [3]. The shift of top V₃Sb layer along the direction of 1/3a - 1/3b will coincide with the bottom one. Due to this shift, the Sb atoms in one layer locate below and above the centers of V triangles in another layer when another half of V triangles in both layers form the distorted octahedra of V atoms (Figs. 1(e) and 2(d)). Such inequivalent local environments of V triangles also lead to the distortion of kagome layers with two kinds of equilateral triangles which have different intralayer V-V distances \( d_{V-V} = 2.7826 \) Å and \( 2.7749 \) Å (green ones) and \( 2.8452 \) Å (red ones). The former one with smaller value could be ascribed to the stronger V-V interactions in the V octahedra. Because of this distortion, the interlayer V-Sb distance \( d_{V-Sb} (= 2.7794 \) Å) fails in between two values of \( d_{V-V} \). In contrast, the interlayer V-V and V-Sb distances \( d_{V-V} = 2.8937 \) Å and \( d_{V-Sb} = 2.8452 \) Å) are much larger than those of \( d_{V-V} \) and \( d_{V-Sb} \), reflecting the relatively weak interlayer interaction when compared to the intralayer one. It has to be noted that the Sb atoms in the kagome layer are slightly move along the c axis and toward to the center of bilayer (see the different z values of V and Sb1 in Table 2). Since there are three Cs, six Sb₂ and three V₃Sb bilayers in one unit cell, we have 3CsV₆Sb₆ = 3Cs + 6Sb₂ + 3 × 2V₃Sb.

CsV₆Sb₁₂ has an orthorhombic symmetry (space group Fmmm, No. 69) with \( a = 5.5564(3) \) Å, \( b = 9.5260(5) \) Å, and \( c = 36.227(2) \) Å (Table 1). Although the structure of CsV₆Sb₁₂ is much more complicated than CsV₃Sb₅ and CsV₆Sb₆, these three materials still share some common structure features. The local environments of Cs layer, Sb₂ layer with Sb2 and Sb3 sites and V₃Sb layer with V1, V2, and Sb1 sites in CsV₆Sb₁₂ (Figs. 1(c), 2(c) and 2(f)) are similar to those in CsV₃Sb₅ and CsV₆Sb₆. But they are compressed along the b axis of orthorhombic lattice (the [210] direction in hexagonal lattice) and it leads to the distortions of these layers with inequivalent intralayer atomic distances, such as \( d_{Cs-Cs} = 5.5564/5.5140 \) Å, \( d_{V-V} = 2.7782/2.7570 \) Å, and \( d_{V-Sb} = 2.8064/2.7850 \) Å (Figs. 2(c) and 2(f)). In addition, such compression also results in the significant movement of Sb atoms in the kagome layer along the c axis (Figs. 1(c) and 1(f) as well as Table 2). Correspondingly, the \( d_{Sb-Sb} \) in both Sb₂ layers above and below the V kagome layer (labelled as Sb₂ layer 1 and layer 2 in Fig. 1(c)) become different. The \( d_{Sb-Sb} \) in Sb₂ layer 1 are 3.1952 Å and 3.1847 Å when those in Sb₂ layer 2 are 3.2494 Å and 3.0777 Å (Fig. 2(e)). The most distinctive structural feature of CsV₆Sb₁₂ is the (VSb)₂ layer with V3 and Sb4 sites between two V₃Sb kagome layers (Figs. 1(c) and 2(g)). In this layer, there are two Sb₂ layers locating below and above a V layer with \( d_{V-Sb} = 2.9324 \) Å. For the former one, the in-plane arrangement of Sb atoms is similar to that in the V₃Sb layer (Fig. 1(f)). For the later one, V atoms form one dimensional (1D) chains along the a direction with \( d_{V-V} = 2.7782 \) Å (Figs. 1(f) and 2(g)), which is exactly same as the value of \( d_{V-V} \) in the V₃Sb layer along the a axis. Actually, such 1D chains of V atoms should lead to the orthorhombic symmetry of CsV₆Sb₁₂. There are two Cs, eight Sb₂, four V₃Sb, and two VSb₂ layers in one unit cell and each layer contains twice atoms when compared to CsV₃Sb₅ and CsV₆Sb₆, thus we have 4CsV₆Sb₁₂ = 2 × [2Cs + 8Sb₂ + 4V₃Sb + 2(VSb₂)].

| TABLE I. Crystallographic data of CsV₆Sb₆ and CsV₆Sb₁₂ at 300 K. |
|-----------------|-----------------|-----------------|
| chemical formula | CsV₆Sb₆ | CsV₆Sb₁₂ |
| space group      | R3m       | Fmmm     |
| crystal system   | rhombohedral | orthorhombic |
| a (Å)            | 5.5575(8) | 5.5564(3) |
| b (Å)            | 5.5575(8) | 9.5260(5) |
| c (Å)            | 35.165(9) | 36.227(2) |
| V (Å³)           | 940.59(36)| 1917.50(18)|
| Z                | 3          | 4          |
| dimens           | 0.05/0.40/0.50 | 0.10/0.36/0.39 |
| calc density (g cm⁻³) | 6.047 | 6.880 |
| abs coeff (mm⁻¹) | 19.270   | 21.971    |
| h                | -7 ≤ h ≤ 7 | -7 ≤ h ≤ 6 |
| k                | -6 ≤ k ≤ 6 | -12 ≤ k ≤ 11 |
| l                | -46 ≤ l ≥ 46 | -46 ≤ l ≤ 48 |
| reflns           | 2536/334/0.0642 | 5846/709/0.0697 |
| data/params/restraints | 334/18/0 | 709/36/0 |
| GOF on P²        | 1.139    | 1.139     |
| R indices (all data) | 0.0825/0.2643 | 0.0590/0.1824 |
| (R1/wR2)²        | 0.0825/0.2643 | 0.0590/0.1824 |
TABLE II. Atomic positions, s.o.f. and equivalent isotropic displacement parameters $U_{eq}$ obtained from the XRD fits for CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ at 300 K.

|       | atom site | $x/a$ | $y/b$ | $z/c$ | s.o.f. | $U_{eq}$ (Å$^2$) |
|-------|-----------|-------|-------|-------|--------|------------------|
| CsV$_6$Sb$_6$ | Cs 3a | 2/3 | 1/3 | 1/3 | 1 | 0.0390(11) |
|       | V Sh | 18Sh | 0.6662(4) | 83331(2) | 0.2009(7) | 1 | 0.0146(10) |
|       | Sh1 | 6c | 2/3 | 1/3 | 0.19918(5) | 0.9548 | 0.0148(9) |
|       | Sh2 | 6c | 1/3 | 2/3 | 0.26503(5) | 0.9685 | 0.0177(8) |
|       | Sh3 | 6c | 0 | 0 | 0.26505(6) | 0.9646 | 0.0183(9) |
| CsV$_8$Sb$_{12}$ | atom site | $x/a$ | $y/b$ | $z/c$ | s.o.f. | $U_{eq}$ (Å$^2$) |
| Cs 4a | 1/2 | 0 | 1/2 | 1 | 0.0239(6) |
| V1 8i | 1/2 | 1/2 | 0.37349(10) | 0.9719 | 0.0041(7) |
| V2 16j | 1/4 | 3/4 | 0.37340(7) | 0.9831 | 0.0068(6) |
| V3 8f | 1/4 | 1/4 | 1/4 | 0.9410 | 0.0089(8) |
| Sh1 8i | 0 | 1/2 | 0.36253(4) | 0.9869 | 0.0077(4) |
| Sh2 16m | 1/2 | 0.66716(10) | 0.43449(3) | 1 | 0.0094(4) |
| Sh3 16m | 1/2 | 0.33846(9) | 0.31147(3) | 1 | 0.0078(4) |
| Sh4 8i | 0 | 0 | 0.22243(4) | 1 | 0.0086(4) |

Figure 3(a) and (b) shows the XRD pattern of a CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ single crystals, respectively. All of peaks can be indexed by the indices of (00l) lattice planes. It indicates that the crystal surfaces are parallel to the $ab$-plane and perpendicular to the caxis for both materials. The insets of Fig. 3(a) and (b) show the photographs of typical CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ crystals on a 1 mm grid paper. It can be seen that the shapes of these two crystals are quite different. For CsV$_6$Sb$_6$ crystals, they have a hexagonal thin-plate-like shape (inset of Fig. 3(a)), consistent with the layered structure and its rhombohedral symmetry. In contrast, for CsV$_8$Sb$_{12}$ crystals, they have a rectangular shape with relatively large thickness. It reflects the orthorhombic distortion of kagome lattice.

Figure 3(c) presents temperature dependence of the zero-field $a$-axis resistivity $\rho_{aa}(T)$ for CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ single crystals. Both of $\rho_{aa}(T)$ curves exhibit similar trend of decreasing with lowering temperature. It clearly indicates that both materials are metals. In addition, the residual resistivity ratio, defined as $\rho_{aa}(300 \text{ K})/\rho_{aa}(2 \text{ K})$, is about 1.94 for CsV$_6$Sb$_6$ when compared to the value of 2.8 for CsV$_8$Sb$_{12}$. It has to be noted that distinctly different from AV$_7$Sb$_5$, the resistivity curves do not show any anomalies in the whole temperature range (2 K - 300 K). Moreover, as shown in Fig. 3(d), again, there are no any transitions in the magnetic susceptibility $\chi(T)$ curves at $\mu_0H = 1 \text{ T}$ with zero-field-cooling (ZFC) mode for $H||c$. These results indicate that the CDW and superconducting transitions are absent in both CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ when $T$ is above 2 K. The $\chi(T)$ curves of both materials exhibit weak temperature-dependence at $T > 50 \text{ K}$ with very small values. Such kind of Pauli paramagnetism is consistent with the itinerant features of electrons in CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ and suggests that the V ions in these materials do not have obvious local moment. The slight upturns of $\chi(T)$ curves at low temperature region could be due to the trace amount of impurities on the surface of crystals. For CsV$_8$Sb$_{12}$, the out-of-plane resistivity $\rho_{cc}$ is much larger than those in-plane ones ($\rho_{aa}$ and $\rho_{bb}$) (Fig. 3(e)), which is reflected in the large anisotropy of resistivity $\gamma_{ca} = \rho_{cc}/\rho_{aa}$ and $\gamma_{cb} = \rho_{cc}/\rho_{bb}$ (Fig. 3(f)). The values of $\gamma_{ca}$ and $\gamma_{cb}$ are about 28 and 30 at 300 K, and increase to 38 and 34 at 2 K. Notably, these $\gamma$ values are larger than that of CsV$_7$Sb$_5$ ($\gamma \sim 10$ at 300 K and 23 at 8 K) [33], suggesting a weaker interlayer coupling in CsV$_8$Sb$_{12}$, i.e., the two-dimensionality is more obvious. On the other hand, the comparable $\gamma_{ca}$ and $\gamma_{cb}$ imply the small in-plane anisotropy of CsV$_8$Sb$_{12}$ even it has a orthorhombic...
FIG. 4. Field dependence of (a, c) MR and (b, d) Hall re-
conductivity.

The slightly smaller \( \rho_{xx} \) than \( \rho_{ab} \) at low temperature could be due to the existence of V chains along
the \( a \)-axis, in which the intrachain hopping could enhance conduc-
tivity.

Cs\( \text{V}_6\text{Sb}_6 \) and Cs\( \text{V}_8\text{Sb}_{12} \) exhibit similar behavior
of magnetoresistance \( \text{MR} = (\rho_{xx}(\mu_0H) - \rho_{xx}(\mu_0H = 9 \text{ T})/\rho_{xx}(\mu_0H = 0)) \) for \( H \parallel c \) and \( \mu \parallel a \). At low temperature,
the MR increases with field gradually and then saturates at high field (Figs. 4(a) and 4(c)). The values
at 2 K and 9 T are about 11 \% and 35 \% for Cs\( \text{V}_6\text{Sb}_6 \) and
Cs\( \text{V}_8\text{Sb}_{12} \). These saturation behaviors of MR with
relatively small high-field values are remarkably different
at 2 K and 9 T are about 11 \% and 35 \% for Cs\( \text{V}_6\text{Sb}_6 \)
and Cs\( \text{V}_8\text{Sb}_{12} \), respectively.

Moreover, different from Cs\( \text{V}_6\text{Sb}_6 \), the low-temperature
\( \rho_{xx}(\mu_0H) \) curve of Cs\( \text{V}_8\text{Sb}_{12} \) has a maximum value. It
shifts to higher fields with increasing temperature and the corresponding field \( H_m \) is larger than 9 T when \( T > 200 \text{ K} \). The Hall coefficient \( R_H(T) \equiv \rho_{yx}(\mu_0H)/\mu_0H \)
determined from the linear fits of \( \rho_{yx}(\mu_0H, T) \) curves
at high-field region. For Cs\( \text{V}_6\text{Sb}_6 \), the \( R_H(T) \) shows a weak temperature dependence (Fig. 4(e)). However, the
\( R_H(T) \) of Cs\( \text{V}_8\text{Sb}_{12} \) is almost unchanged when \( T \leq 75 \text{ K} \)
and then increases at higher temperature with changing
the sign from negative to positive at 225 K. Because
of the saturation behavior of MR, this temperature
dependence and sign change of \( R_H(T) \) should not
be ascribed to the type change of dominant carriers at
high temperature but be explained by the shift of low-
field part of \( R_H \) with \( H < H_m \) to 9 T. For this region,
carrier mobility \( \mu \) has a significant influence on \( R_H \) according to the two-band model \[30\]. At 2 K, we
evaluate the apparent carrier concentration \( n_a \) using the formula |
\( R_H = 1/|e|n_a \) and it is \( 6.18(1) \times 10^{21} \text{ cm}^{-3} \)
and \( 2.718(8) \times 10^{21} \text{ cm}^{-3} \) for Cs\( \text{V}_6\text{Sb}_6 \)
and Cs\( \text{V}_8\text{Sb}_{12} \), respectively. In addition, according to the single-band
model, the value of \( \mu \) can be calculated using the formula
\( \mu = \sigma_{xx}(0)/|e|n_a \approx 1/|e|n_a|\rho_{xx}(0) = R_H/\mu_{xx}(0) \),
The temperature dependence of derived \( \mu(T) \) for both
compounds is presented in Fig. 4(f). For Cs\( \text{V}_6\text{Sb}_6 \), the
\( \mu(T) \) is small \( 6.07(1) \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \) at 2 K and insen-
tive to temperature, implying that the dominant scat-
ering mechanism may be the electron-impurity scattering.
In contrast, for Cs\( \text{V}_8\text{Sb}_{12} \), the \( \mu(T) \) increases with
decreasing temperature in general and reaches \( 27.32(8) \)
\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1} \) at 2 K. It suggests that the electron-phonon
scattering mechanism should be the dominant and the
decreased scatting rate because of the gradually frozen
phonons at low temperature enhances \( \mu(T) \) \[30\]. It has
to be noted that the values of \( n_a \) and \( \mu \) for both Cs\( \text{V}_6\text{Sb}_6 
and Cs\( \text{V}_8\text{Sb}_{12} \) are lower than those in Cs\( \text{V}_3\text{Sb}_5 \)
\[23\], explaining well their much larger low-temperature resistivity
than the latter \[23\]. Moreover, the drastic changes
of \( n_a \) and \( \mu \) of Cs\( \text{V}_6\text{Sb}_6 \) and Cs\( \text{V}_8\text{Sb}_{12} \) when compared
with Cs\( \text{V}_3\text{Sb}_5 \) reflect their obviously different electronic
structures and Fermi surfaces near Fermi energy level \( E_F \),
originating from their different structures. These changes
also explain the absence of CDW and superconductivity
in the former materials partially because the \( E_F \) may
have moved away from the van Hove singularity near the
M point of Brillouin zone.
CONCLUSION

In summary, single crystals of two new members of V-based kagome metals CsV$_6$Sb$_6$ and CsV$_8$Sb$_{12}$ are grown successfully. Transport and magnetization measurements indicate that both materials show metallic behaviors and Pauli paramagnetism without CDW and superconducting transitions down to 2 K. The discovery of new V-based kagome metals proves that the kagome lattice of transition metal can be incorporated into more complicated structures. The structural flexibility of V-based kagome metals provides a new platform to study the possible correlated topological phenomena in this kind of materials.

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