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# Non-trivial Fermi surface topology of kagome superconductor $\text{CsV}_3\text{Sb}_5$ probed by de Haas-van Alphen oscillations

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We have investigated the normal state Fermi surface properties of the kagome superconductor  $\text{CsV}_3\text{Sb}_5$  using torque magnetometry with applied fields ( $H$ ) up to 35 T. The torque signal shows clear de Haas-van Alphen (dHvA) oscillations above 15 T. The oscillations are smooth and consist of seven distinct frequencies with values from  $\sim 18$  T to 2135 T. The presence of higher-frequencies in  $\text{CsV}_3\text{Sb}_5$  is further confirmed by carrying out additional measurements using the tunnel diode oscillator (TDO) technique. All frequencies measured at different tilt angles ( $\theta$ ) of the field direction with respect to the  $c$ -axis show a  $1/\cos\theta$ -dependence, implying that the Fermi surfaces corresponding to these frequencies are two-dimensional. The absence of dHvA oscillations at  $\theta = 90^\circ$  further supports the presence of 2D Fermi surfaces. The Berry phase ( $\phi$ ) determined from the Landau level fan diagram for all frequencies is  $\sim 0.4$ . This value is close to the theoretical value of  $\phi = 0.5$  for a non-trivial system, which strongly supports the non-trivial topology of the Fermi surfaces of these frequencies. Several quantities characterizing the Fermi surface are calculated employing the Lifshitz-Kosevich theory. These findings are crucial for exploring the interplay between non-trivial band topology, charge density wave, and unconventional superconductivity of  $\text{CsV}_3\text{Sb}_5$ .

## I. INTRODUCTION

The recent discovery of superconductivity ( $T_c \sim 0.3 - 3$  K) in a new class of quasi-two-dimensional kagome metals  $\text{AV}_3\text{Sb}_5$  ( $A = \text{K}, \text{Rb}, \text{and Cs}$ ) has attracted enormous attention[1–4]. These materials crystallize in a hexagonal lattice with the  $P6/mmm$  space group[1, 5]. Transport and magnetization measurements on these materials have shown a clear anomaly at  $T_{CDW} \sim 80 - 110$  K arising due to the charge density wave (CDW) ordering. Theoretical calculations and angle-resolved photoemission spectroscopy (ARPES) have shown that there are several Dirac points near the Fermi level with a non-zero  $Z_2$  topological invariant [1–3]. Therefore,  $\text{AV}_3\text{Sb}_5$  materials provide unique platforms for exploring the interplay between superconductivity (SC), CDW, and non-trivial band topology[5–8]. Recently, a robust zero-bias conductance peak was observed[9] inside the superconducting vortex in  $\text{CsV}_3\text{Sb}_5$  which suggests that this material could be an ideal candidate for topological superconductivity.

Most of the studies in these systems are focused on the superconductivity and its relation with CDW. There exist limited reports[4, 10, 11] on the Fermi surface properties, especially via quantum oscillations, although it is one of the crucial methods for investigating the Fermi surface properties and its topology. The reasons could

be the requirements of high-quality single crystals and high magnetic fields (typically above 10 T) to observe Landau level quantization in  $\text{AV}_3\text{Sb}_5$ . In previous Shubnikov de-Haas (SdH) oscillations studies[10] in  $\text{CsV}_3\text{Sb}_5$ , only low frequencies (below 500 T) were observed. However, recent SdH oscillations studies by B. R. Ortiz et al.[12] and Y. Fu et al.[13] with applied fields up to 14 T and 32 T, respectively, showed multiple high frequencies (above 500 T) in addition to the low frequencies reported earlier[10]. Therefore, the exact number of frequencies, and hence the Fermi surface properties of  $\text{CsV}_3\text{Sb}_5$  are not yet well understood. Moreover, angle dependence, temperature dependence, and Berry phase calculations, which are used to determine the Fermi surface dimensionality, properties, and topology have not been performed in previous studies[10, 12, 13], especially for higher frequencies. Hence, more detailed studies even at higher fields are needed to better understand the Fermi surface properties and topology of  $\text{CsV}_3\text{Sb}_5$ .

This work focuses on investigating the Fermi surface of  $\text{CsV}_3\text{Sb}_5$  using torque magnetometry at low temperature down to 0.32 K under applied fields up to 35 T. The torque signal clearly shows the de Haas-van Alphen (dHvA) oscillations with seven distinct frequencies with values ranging from  $\sim 6$  T to 2135 T, and four of them are above 500 T. The presence of higher frequencies is further confirmed by additional tunnel diode oscillator (TDO) measurements. Our detailed angle-dependence of dHvA oscillations and Berry phase calculations reveal the presence of 2D Fermi surfaces with non-trivial topology in  $\text{CsV}_3\text{Sb}_5$ .

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† Equal contribution

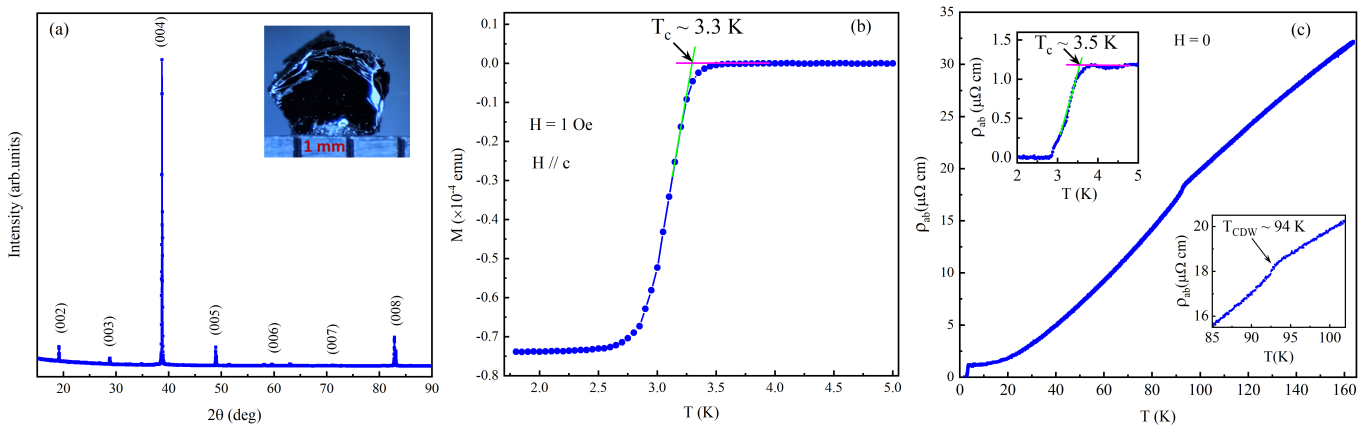


FIG. 1. **X-ray Diffraction (XRD), Magnetization, and Resistivity:** (a) The room temperature XRD pattern of  $\text{CsV}_3\text{Sb}_5$  single crystal indexed in the  $P6/mmm$  structure. Inset: An optical image of a typical  $\text{CsV}_3\text{Sb}_5$  single crystal placed beside a millimeter scale. (b) Temperature dependence of magnetization,  $M(T)$ , measured by applying  $H = 1$  Oe along the  $c$ -axis. (c) Temperature dependence of electrical resistivity  $\rho_{ab}(T)$  of  $\text{CsV}_3\text{Sb}_5$  displaying the CDW transition at 94 K. Upper left inset:  $\rho_{ab}(T)$  versus  $T$  at low temperature exhibiting the superconducting transition with  $T_c \sim 3.5$  K. Lower right inset:  $\rho_{ab}(T)$  versus  $T$  plot showing the charge density wave transition,  $T_{CDW} \sim 94$  K.

## II. EXPERIMENTAL PROCEDURE

Single crystals of  $\text{CsV}_3\text{Sb}_5$  were grown via the flux method similar to that described in earlier studies[1, 3]. The crystals were then characterized by x-ray diffraction (XRD), magnetization and resistivity measurements. The XRD measurement was performed in a PANalytical XPert Pro diffractometer. Energy dispersive spectroscopy (EDS) measurements show the near stoichiometry of our single crystals (Fig. S1 in Supplemental Material[14]). Magnetization measurements were carried out in a magnetic properties measurement system (MPMS-7 T, Quantum Design). Electrical resistivity measurements were performed in a physical properties measurement system (PPMS-9 T, Quantum Design) following a standard four-probe method.

High-field measurements were performed at the National High Magnetic Field Laboratory (NHMFL), Tallahassee, Florida, with applied fields as high as 35 T in a dc resistive water-cooled magnet and top-loaded into a 3-He cryostat allowing for sample temperatures of  $\sim 0.3$  - 60 K. A single crystal of  $\text{CsV}_3\text{Sb}_5$  was mounted on the rotating platform and slowly cooled down to a base temperature of 0.32 K. The sample was rotated in an applied magnetic field between  $H \parallel c$ -axis ( $\theta = 0^\circ$ ) to  $H \parallel ab$ -plane ( $\theta = 90^\circ$ ) in increments of  $10^\circ$ . Magnetic fields were swept at each fixed temperature at a rate of 2.2 T/min. Torque magnetization measurements with a miniature piezoresistive cantilever were used to observe dHvA oscillations where the sample was fixed to the cantilever arm with vacuum grease. Two resistive elements on the cantilever were incorporated with two room-temperature resistors forming a Wheatstone bridge, which was balanced at base temperature before sweeping the magnetic field. A TDO circuit (i.e., self-resonating LC circuit) was used where the sample was placed inside the circuit inductor.

The resonant frequency of the circuit is measured, which changes with the magnetic susceptibility of the sample.

## III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1(a) displays the room temperature XRD pattern of  $\text{CsV}_3\text{Sb}_5$  single crystal indexed in the hexagonal structure with space group  $P6/mmm$ . An optical image of a typical  $\text{CsV}_3\text{Sb}_5$  single crystal is presented in the inset of Fig. 1(a). The flat surface corresponds to the  $ab$  basal plane, confirmed by XRD which shows (0 0 1) peaks only. Fig. 1(b) shows the zero-field cooled (ZFC) temperature dependence of magnetization,  $M(T)$ , between 1.8 to 5 K measured in an applied magnetic field of 1 Oe along the  $c$ -axis. A sharp transition in  $M(T)$  is observed with an onset of  $T_c \sim 3.3$  K. Fig. 1(c) shows the temperature dependence of the electrical resistivity,  $\rho_{ab}(T)$ , measured along the  $ab$  plane which exhibits the CDW transition at 94 K (lower right inset) and a superconducting transition with  $T_c \sim 3.5$  K (upper left inset). Both the CDW transition temperature and  $T_c$  are consistent with the previously reported values [1, 3] for  $\text{CsV}_3\text{Sb}_5$ . Note that the  $T_c = 3.5$  K we observed here is higher than  $T_c = 2.5$  K in the previous reports[1, 3].

In order to investigate the Fermi surface properties of  $\text{CsV}_3\text{Sb}_5$ , we measured the magnetic torque ( $\tau$ ) at very high fields up to 35 T. Fig. 2(a) shows the  $\tau$  vs  $H$  plot for two  $\text{CsV}_3\text{Sb}_5$  single crystals, S1 and S2, at 0.32 K at tilt angle ( $\theta$ ) =  $0^\circ$ . The  $\tau$  signal increases with  $H$  and shows clear dHvA oscillations above 15 T. The quantum oscillations are clearly visible in both S1 and S2, and our calculations showed that both samples have comparable frequencies (Fig. S2 in Supplemental Material[14]). However, as oscillations are more pronounced in S1 compared

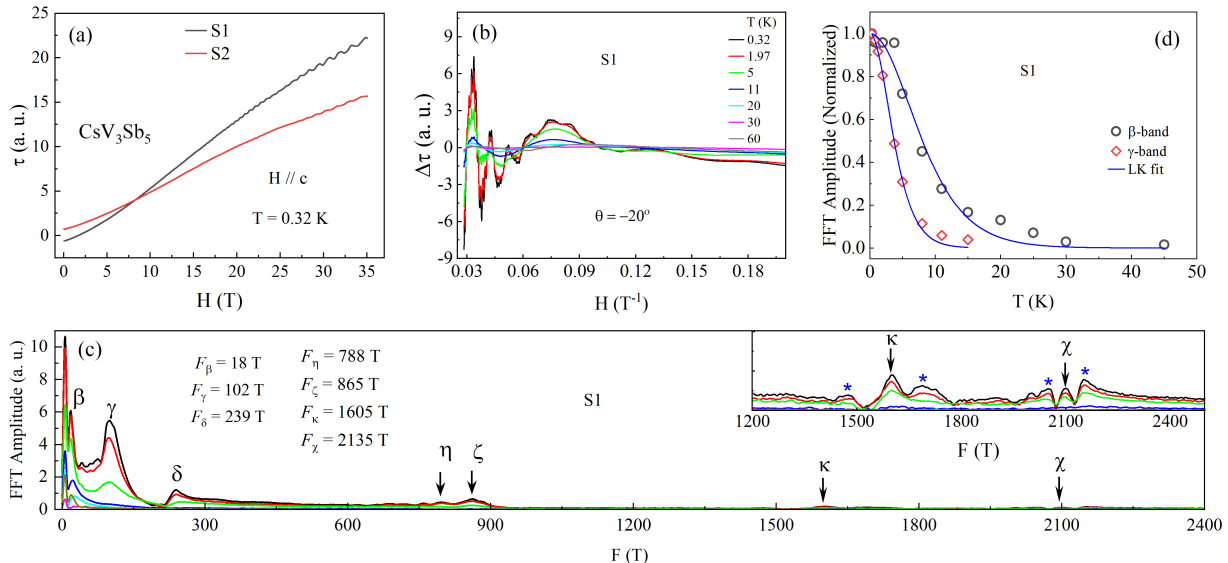


FIG. 2. **de Haas-van Alphen (dHvA) oscillations, Fourier transform, and Lifshitz-Kosevich (LK) Fit:**(a) Magnetic field dependence of magnetic torque ( $\tau$ ) for the two for CsV<sub>3</sub>Sb<sub>5</sub> single crystals, S1 and S2, at 0.32 K under applied fields up to 35 T. For both S<sub>1</sub> and S<sub>2</sub>, the  $\tau$  value increases monotonically with the applied field and shows clear de Haas-van Alphen (dHvA) oscillations above 15 T. (b) Background subtracted torque data for S1 at selected temperatures. The amplitude of the oscillations gradually decreases at higher temperatures and completely disappears at 60 K. (c) The frequency spectra of the oscillations data shown in (b). There are seven distinct frequencies ranging from 6 to 2135 T. Inset: The FFT spectra in the range (1200 - 2500 T) for better visibility of the  $F_{\kappa}$  and  $F_{\chi}$  frequencies. There are a few additional frequencies as denoted by asterisks which disappear quickly at higher temperatures and  $\theta$ -values. (d) Temperature dependence of the FFT amplitudes for the  $\beta$  and  $\gamma$  frequencies. The solid curves represent the best fit to the data using the LK formula [Eq. 1].

to those in S2, we have chosen S1 for further temperature and angle-dependence experiments and data analyses. In addition, we rotated the sample in the magnetic field and found that the dHvA oscillations are more pronounced at  $\theta = -20^\circ$ . Therefore, we have carried out temperature dependence analyses of dHvA oscillations at  $\theta = -20^\circ$ . This point is further discussed in the angle-dependence data later. Fig. 2(b) shows the background subtracted oscillations at  $\theta = -20^\circ$  at different temperatures. The amplitude of oscillations gradually decreases at higher temperatures, and it completely disappears at 60 K. The oscillations are smooth, well-defined and appear to have more than one frequency. The frequency of the dHvA oscillations can be calculated by taking a fast Fourier transform (FFT).

Fig. 2(c) shows the Fourier transform of the data shown in Fig. 2(b). There are seven distinct frequencies: four of them are low frequencies ( $F_{\beta} = 18 \pm 3$  T,  $F_{\gamma} = 102 \pm 13$  T, and  $F_{\delta} = 239 \pm 16$  T) and the remaining four ( $F_{\eta} = 788 \pm 21$  T,  $F_{\zeta} = 865 \pm 23$  T,  $F_{\kappa} = 1605 \pm 120$  T, and  $F_{\chi} = 2135 \pm 90$  T) are high frequencies. The low frequencies in CsV<sub>3</sub>Sb<sub>5</sub> were already reported by F. H. Yu et al.[10] using SdH oscillations, and they are in close agreement with our data. There are no published reports of higher frequencies in CsV<sub>3</sub>Sb<sub>5</sub> yet. Recently, Y. Fu et al.[13] and B. R. Ortiz et al.[12] claimed the presence of higher frequencies up to 2000 T using SdH oscillations with applied fields up to 32 T. All the frequencies in our

dHvA oscillations are in good agreement with those obtained by SdH oscillations[10, 12, 13]. We noticed that some of the frequencies, especially lower frequencies, in our data were not observed in previous reports[10, 12, 13] and when observed, the values are slightly different. This small variation could be due to (i) the quality of single crystals, (ii) the different measurement technique we used here (torque magnetometry instead of magnetoresistance) and also could be related to the sensitivity of these measurement techniques and (iii) these frequencies are at  $\theta = -20^\circ$  not at  $0^\circ$  as in those reports[10, 12, 13]. The higher frequencies disappear above 8 K, whereas the lower frequencies persist even up to 30 K, which is consistent with recent reports[12, 13]. Note that the presence of additional shoulders on either side of the  $\kappa$  and  $\chi$  frequencies as denoted by the asterisks. These peaks disappear quickly at higher temperatures and  $\theta$ -values. Therefore, we could not carry out further analyses to estimate the effective masses and other relevant properties corresponding to them. We noticed that such features were also observed in the FFT spectrum of the previous work[12] and was reported as likely extrinsic effect. Torque measurements even at higher magnetic fields (above 35 T) might help to resolve the origin of these peaks and understand their Fermi surface properties.

The frequency ( $F$ ) of quantum oscillations is directly proportional to the Fermi wave vector  $k_F$  as described assuming circular extremal orbits in Onsager's



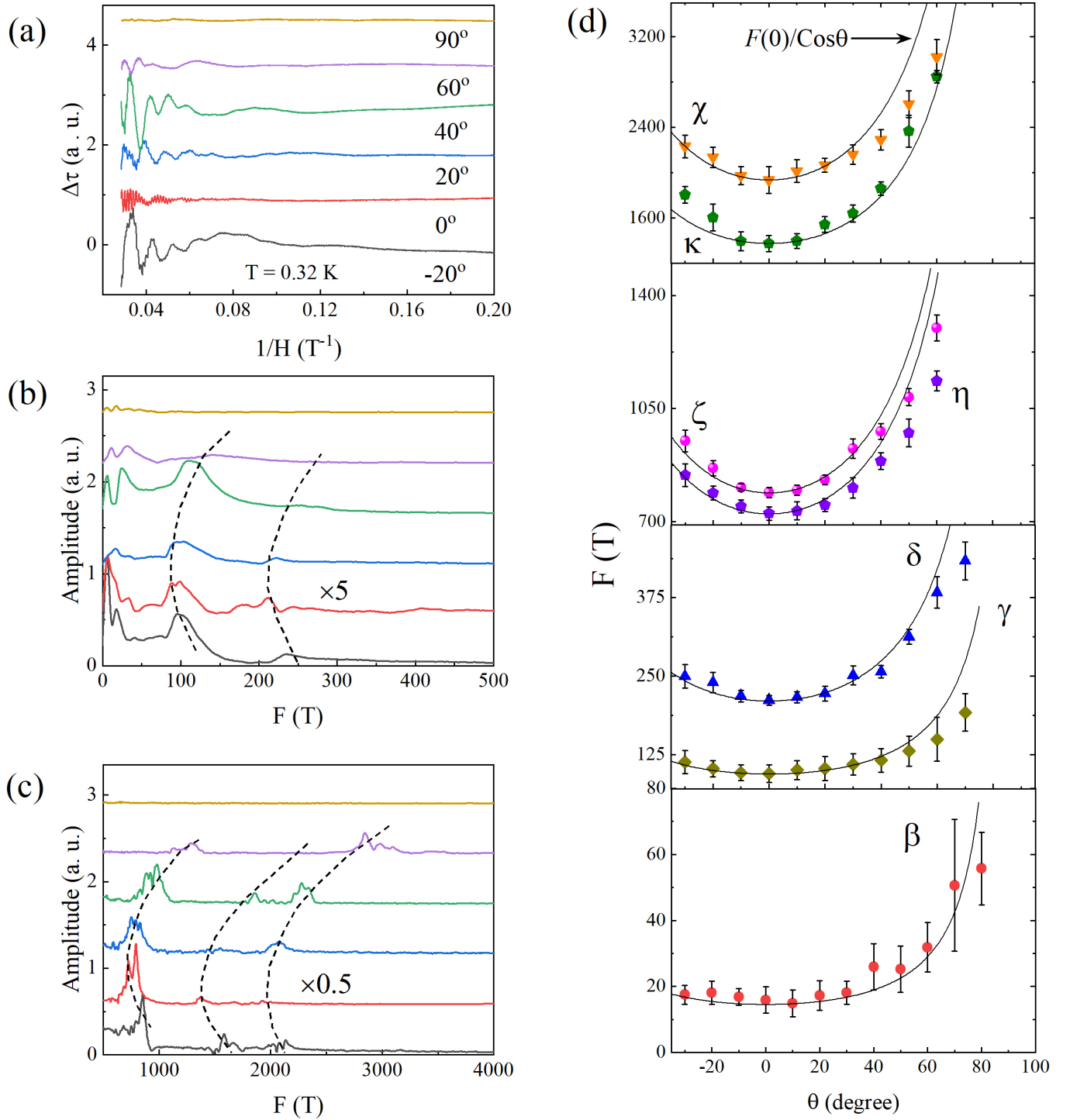


FIG. 3. **Angle-dependent de Haas van Alphen (dHvA) oscillations:**(a) Background subtracted torque data for CsV<sub>3</sub>Sb<sub>5</sub> at selected tilt angles ( $\theta$ ) at 0.32 K. The amplitude of the oscillations decreases at higher  $\theta$  values and completely disappears at 90°, strongly suggesting the two-dimensional nature of the Fermi surface. The FFT spectrum of the data shown in (a) in the range (b) 0 - 500 T and (c) 500 - 4000 T. The FFT data at 0° are multiplied by the factors 5 and 0.5 in (b) and (c), respectively, for better visibility. The curves in (a), (b), and (c) are shifted vertically for clarity. (d) The frequency vs. angle plots for all the bands. All frequencies can be clearly resolved up to 70°, and they show  $F(0)/\cos\theta$ -dependence (solid curves), which strongly suggest that the Fermi surfaces corresponding to these frequencies are two-dimensional. The error bar for each data point in (d) is defined as the half-width at half-maximum (HWHM) of the respective peak in the frequency plot. The dashed-curves/line are a guide for the eye.

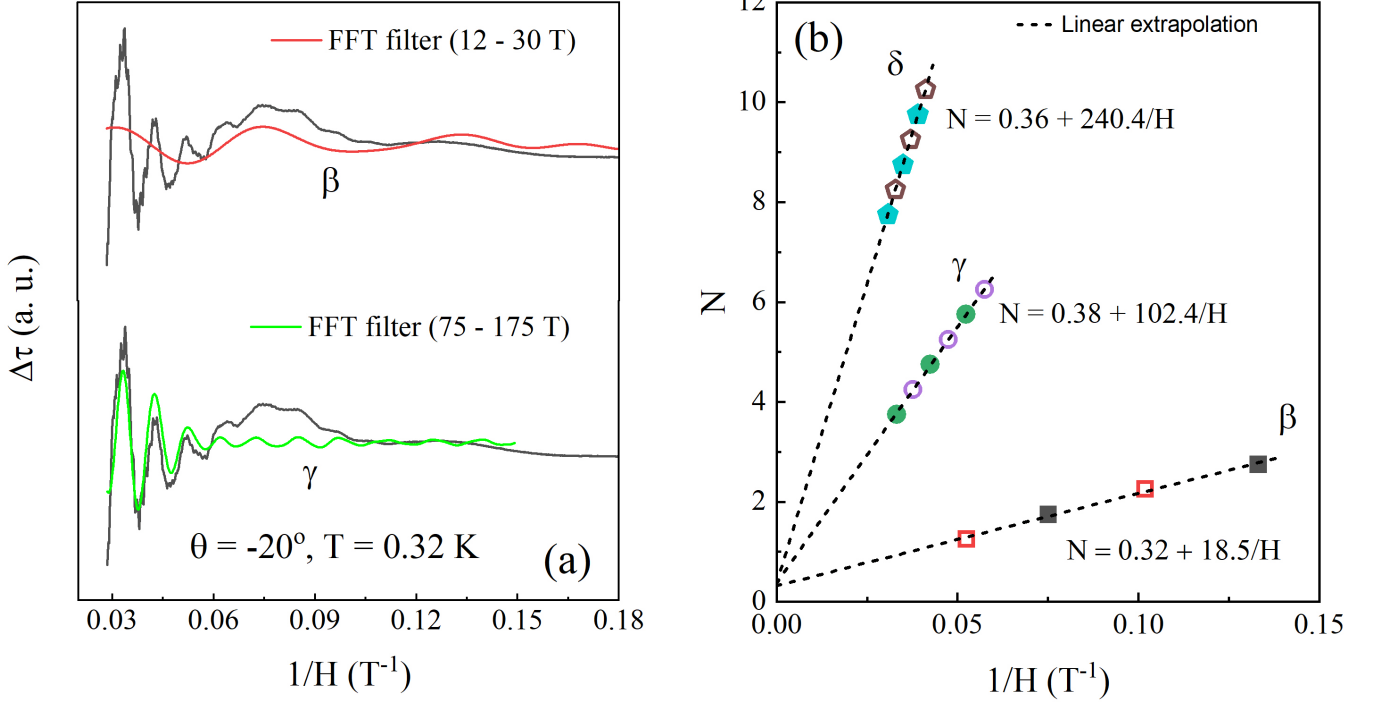


FIG. 4. **The bandpass filter and Landau level (LL) fan diagram.** (a) Separation of the dHvA oscillations corresponding to  $F_\beta$  and  $F_\gamma$  frequencies using the band pass filters of (12 - 30 T) and (75 - 175 T). The black curves are the raw data, and the red and green curves are the filtered data for the  $\beta$  and  $\gamma$ -bands, respectively. (b) Landau-level (LL) fan diagram for  $\beta$ ,  $\gamma$ , and  $\delta$  frequencies. Minima and maxima of the oscillations are assigned to the  $(N + 1/4)$  and  $(N - 1/4)$ , respectively, for constructing the LL plot. The dashed-lines are linear extrapolation of the data in the limit  $1/H \rightarrow 0$ .

relation[15, 16]  $F = \hbar/(2e)k_F^2$ , where  $\hbar$  is the Planck's constant and  $k_F$  is the Fermi wave-vector. Therefore, the presence of seven frequencies implies that there are seven Fermi wave vectors corresponding to each frequency and that CsV<sub>3</sub>Sb<sub>5</sub> has complex Fermi surfaces with several pockets. In addition, the amplitude of these frequencies decreases at higher temperatures as can be explained by the Lifshitz-Kosevich (LK) formula[15],

$$\Delta\tau(T, H) \propto e^{-\lambda_D} \frac{\lambda(T/H)}{\sinh[\lambda(T/H)]}, \quad (1)$$

with  $\lambda_D(H) = \frac{2\pi^2 k_B}{\hbar e} m^* \frac{T_D}{H}$  and  $\lambda(T/H) = \frac{2\pi^2 k_B}{\hbar e} m^* \frac{T}{H}$ . Here,  $T_D$ ,  $k_B$  and  $m^*$  represent the Dingle temperature, Boltzmann's constant, and effective mass of the charge carriers, respectively. The first term is the Dingle factor, which describes attenuation of the oscillations with decreasing field  $H$ . The second term explains the weakening of the oscillations at higher temperatures. Due to the presence of multiple frequencies in our data, it is difficult to exactly extract the oscillation amplitude from raw data [Fig. 2(b)]. Therefore, we have taken the temperature dependence of the FFT amplitudes for estimating  $m^*$  of the charge carriers. Fig. 2(d) shows the normalized FFT amplitudes for the  $\beta$  and  $\gamma$  bands at different temperatures. As seen in the graph, the FFT amplitude decreases with temperature, which can be described by the LK formula [Eq. (1)] as shown by the

solid curve. Here, the parameter  $H$  used in LK fit is taken as 8.75 T, which is the harmonic mean of the inverse fields of the FFT interval[13, 17, 18]. From the best-fit parameters, we have estimated an effective mass for the  $\beta$  and  $\gamma$ -bands to be  $m_\beta^* = (0.160 \pm 0.123)m_o$  and  $m_\gamma^* = (0.346 \pm 0.065)m_o$ , where  $m_o$  is the free electron mass. Following the same procedure, we have calculated  $m_\delta^* = (0.327 \pm 0.013)m_o$ ,  $m_\eta^* = (0.302 \pm 0.004)m_o$ ,  $m_\zeta^* = (0.312 \pm 0.005)m_o$ ,  $m_\kappa^* = (0.240 \pm 0.009)m_o$ , and  $m_\chi^* = (0.233 \pm 0.014)m_o$  (Fig. S2 in Supplemental Material[14]). These mass values are slightly heavier than those reported by Yu et al.[10] and Ortiz et al.[12] but comparable with those reported by Fu et al.[13] for CsV<sub>3</sub>Sb<sub>5</sub> (Tab. S1 in Supplemental Material [14]). Effective masses reported for other systems (KV<sub>3</sub>Sb<sub>5</sub> and RbV<sub>3</sub>Sb<sub>5</sub>)[4, 11] are also comparable with our results.

Angle-dependent dHvA oscillations provide information about the shape, size, and dimensionality of the Fermi surface. Therefore, we have rotated the sample in situ and measured the torque signal as a function of  $\theta$ . Fig. 3 (a) shows the  $\Delta\tau$  versus  $1/H$  plot for CsV<sub>3</sub>Sb<sub>5</sub> at selected  $\theta$  values. As seen in the graph, the amplitude of the oscillations varies with  $\theta$ . The oscillations are more pronounced at  $\theta = -20^\circ$  and gradually decrease as we rotate the sample towards  $\theta = 0^\circ$ . Also, the amplitude of these oscillations gradually increases with  $\theta$ , reaching a maximum near  $\theta = 40^\circ$ , and then decreases

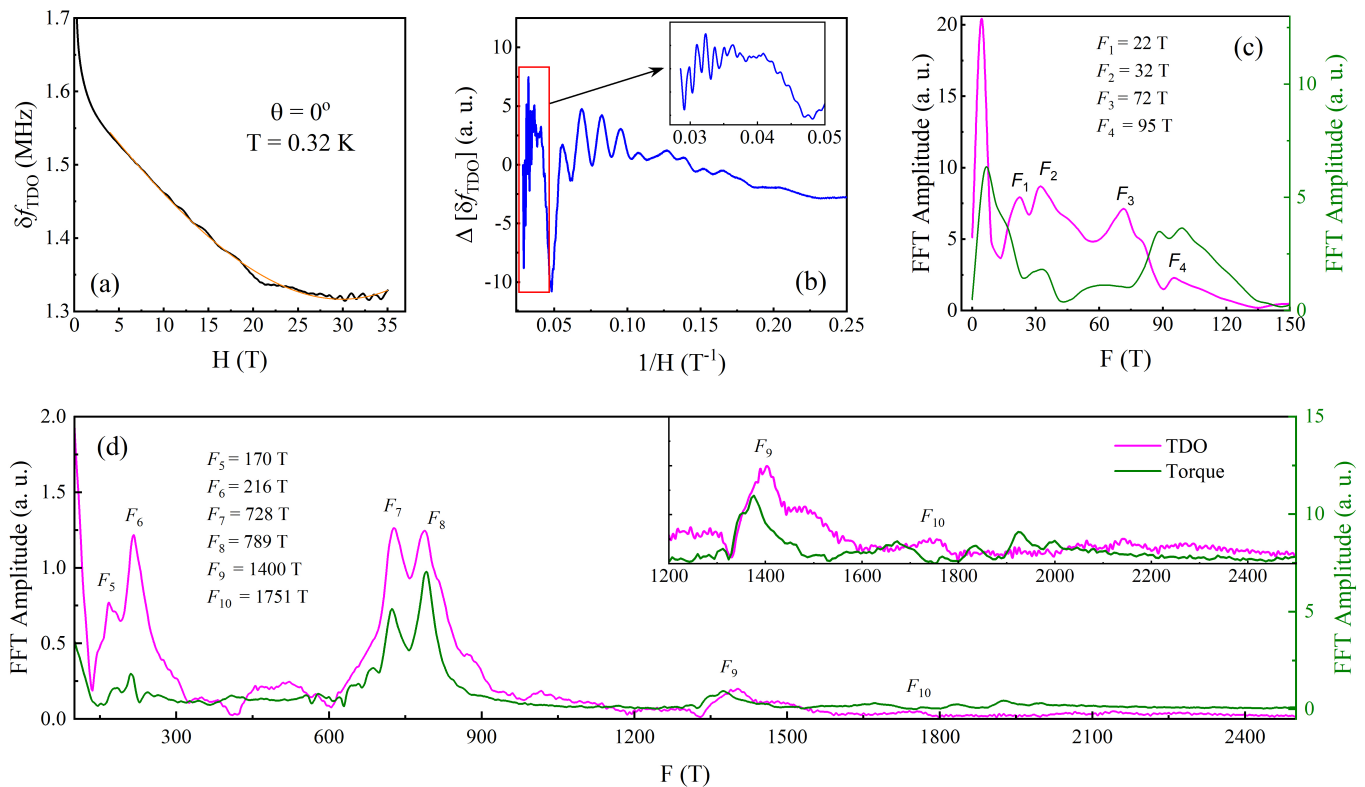


FIG. 5. **Tunnel diode oscillation (TDO)**. (a) Resonant frequency,  $\delta f_{TDO}$  versus  $H$  data for  $\text{CsV}_3\text{Sb}_5$  with applied fields up to 35 T at  $T = 0.32$  K and  $\theta = 0^\circ$ . The TDO signal clearly shows oscillations above 10 T. The solid orange curve is the best-fit curve to data using the Chebyshev polynomial for background subtraction. (b) The oscillatory part of the TDO signal after background subtraction. The quantum oscillations are smooth and well defined with different periods. The inset shows zoom-in  $1/H$  from 0.027 to 0.05  $\text{T}^{-1}$ . The frequency spectra of the oscillations shown in (b) in the range (0 to 150 T) (c) and (100 to 2500 T) (d). There are ten distinct frequencies ranging from  $\sim 4.6$  T to 1751 T. The frequencies obtained from torque measurements at  $\theta = 0^\circ$  are also included for the comparison. The inset in (d) represents the FFT spectra in the range (1200 - 2500 T) for better visibility.

again at higher  $\theta$  values. No oscillations are observed at  $\theta = 90^\circ$ , strongly suggesting the presence of a 2D Fermi surface[16, 19, 20] in  $\text{CsV}_3\text{Sb}_5$ .

Notice that the period of the dHvA oscillations changes with  $\theta$ , which means the frequency also varies with  $\theta$ . Employing a fast Fourier transform, we have determined the frequencies at different  $\theta$  values and then presented them in Figs. 3(b) and (c). As expected, the frequency changes with  $\theta$ , as indicated by the dashed lines. No frequencies are observed (except  $F_\alpha$ ) at  $\theta = 90^\circ$  further supporting that the Fermi surfaces are two-dimensional in  $\text{CsV}_3\text{Sb}_5$ .

Angle dependence of the frequencies is plotted in Fig 3(d). All frequencies ( $F_\beta$ ,  $F_\gamma$ ,  $F_\delta$ ,  $F_\eta$ ,  $F_\zeta$ ,  $F_\kappa$ , and  $F_\chi$ ) vary with  $\theta$ , as shown in Fig. 3(d). The angle-dependence of these frequencies can be described by  $F(0)/\cos\theta$ , where  $F(0)$  is the frequency at  $\theta = 0^\circ$ , as shown by the solid curves. This provides strong evidence for a 2D Fermi surface[16, 19] in  $\text{CsV}_3\text{Sb}_5$ . The cosine-dependence of some of the lower frequencies ( $< 1000$  T) in  $\text{CsV}_3\text{Sb}_5$  has been reported in previous studies[12, 13] too. Here, we demonstrate that even the higher frequen-

cies ( $> 1000$  T) follow cosine-dependence, strongly supporting 2D Fermi surfaces of those frequencies.

Absence of the dHvA oscillations (and frequencies) at  $\theta = 90^\circ$  and the cosine-dependence of the frequencies already revealed the presence of a 2D Fermi surfaces in  $\text{CsV}_3\text{Sb}_5$ . To solidify this point further, we have estimated the Berry phase ( $\phi$ ) which can be calculated by constructing a Landau level (LL) fan diagram[15, 16, 21]. The  $\phi$  value is  $\pi$  for the topologically non-trivial, and 0 for trivial systems[16]. Due to the presence of multiple frequencies, it is not easy to separate the dHvA oscillations for individual frequencies and construct a LL fan diagram. One approach in such a case is to use a band pass filter and separate the oscillations only corresponding to a specific frequency. This method has been used successfully to determine the  $\phi$  values in many topological systems[22–25]. The solid red and green curves in Fig. 4(a) represent the dHvA oscillations for the  $\beta$  and  $\gamma$ -bands separated from raw data (the black curve) using bandpass filters of (12 - 30 T) and (75 - 175 T), respectively.

Fig. 4(b) shows the LL fan plots for the  $\beta$ ,  $\gamma$  and

TABLE I. Physical parameters: the frequency ( $F$ ), Fermi surface area ( $S_F$ ), Fermi wave vector ( $k_F$ ), effective mass ( $m^*$ ), Fermi velocity ( $v_F$ ), Dingle temperature  $T_D$ , quantum relaxation time ( $\tau_s$ ), mean free path ( $l_{2D}$ ) and quantum mobility ( $\mu$ ), characterizing the dHvA oscillations of CsV<sub>3</sub>Sb<sub>5</sub>.

Band	$F$ (T)	$k_F$ ( $\text{\AA}^{-1}$ )	$S_F$ ( $\text{\AA}^{-2}$ )	$m^*/m_o$	$v_F$ ( $10^4 \text{ ms}^{-1}$ )	$T_D$ (K)	$\tau_s$ ( $10^{-13}$ s)	$l_{2D}$ (nm)	$\mu$ ( $m^2V^{-1}s^{-1}$ )
$\beta$	18	0.023	0.172	0.160	16.858	3.2	3.781	63.746	0.414
$\gamma$	102	0.056	0.973	0.346	18.558	4.6	2.630	48.815	0.133
$\delta$	239	0.085	2.279	0.327	30.057	4.8	2.521	75.770	0.135
$\eta$	788	0.155	7.516	0.302	59.095	0.8	1.512	893.822	0.878
$\zeta$	865	0.162	8.250	0.312	59.931	4.4	2.750	164.811	0.154
$\kappa$	1605	0.221	15.308	0.240	106.127	5.9	2.051	217.650	0.150
$\chi$	2135	0.255	20.363	0.233	126.079	1.3	9.308	1173.504	0.701

$\delta$  bands. For the dHvA oscillations in magnetization ( $M$ ), the minima and maxima are assigned ( $N - \frac{1}{4}$ ) and ( $N + \frac{1}{4}$ ), respectively while constructing the LL fan plot[22, 23], where  $N$  represents the LL index. Since  $\vec{\tau} = \vec{M} \times \vec{H}$ , the oscillations in torque signal can be either in- or out-of-phase with the oscillations in magnetization[25]. From the relation[15],  $\tau = -\frac{1}{F} \frac{dF}{d\theta} M_{\parallel} H$ , where  $M_{\parallel}$  is the component of  $M$  along  $H$ , the dHvA oscillations in  $\tau$  will be in-phase with  $M$  if the frequency slope is negative ( $\frac{dF}{d\theta} < 0$ ) and out-of-phase if  $\frac{dF}{d\theta} > 0$ . In our frequency vs.  $\theta$  plot in Fig. 3(d), all the frequencies show positive slope ( $\frac{dF}{d\theta} > 0$ ). Therefore, we have assigned ( $N + \frac{1}{4}$ ) for minima and ( $N - \frac{1}{4}$ ) for maxima in the construction of the LL fan diagram (Fig. 4(b)). From the linear extrapolation in the limit  $1/H \rightarrow 0$  in the LL fan diagram, we have obtained  $\phi = 0.32 \pm 0.09$ ,  $0.38 \pm 0.05$ , and  $0.36 \pm 0.01$  for the  $\beta$ ,  $\gamma$  and  $\delta$ -bands, respectively. This  $\phi$  value is very close to the theoretical value of 0.5 for a topologically non-trivial system[16, 21, 26]. In addition, the linear extrapolation gives frequency values of ( $18.5 \pm 0.9$ ) T, ( $102.4 \pm 1.1$ ) T, and ( $240.4 \pm 0.4$ ) T for the  $\beta$ ,  $\gamma$  and  $\delta$ -bands, respectively. These frequency values are in close agreement with  $F_{\beta} = 18$  T,  $F_{\gamma} = 102$  T,  $F_{\delta} = 239$  T obtained from the Fourier transform (Fig. 2(c)). This implies that the technique of separating the dHvA oscillations using the bandpass filter still preserves the original signal. The  $\phi$  value varies slightly depending on the range of the bandpass filter (Fig. S4 in Supplemental Material[14]). Therefore, we have selected the filter that provides the frequency value that matches the FFT spectrum (Fig. 2). Following the same procedure, we have estimated the  $\phi$  values of  $\sim 0.4$  for the remaining frequencies (Fig. S5 in Supplemental Material[14]). Recent SdH oscillations studies[13] on CsV<sub>3</sub>Sb<sub>5</sub> have also reported non-trivial  $\phi$  values for two of the frequencies

(73 T and 727 T). The  $\phi$  value close to 0.5 in our data further confirms non-trivial band topology in CsV<sub>3</sub>Sb<sub>5</sub>.

From our angle-dependence and Berry phase analyses, we have proved the presence of 2D Fermi surfaces in CsV<sub>3</sub>Sb<sub>5</sub>. To determine various physical parameters characterizing the Fermi surface, we have estimated the Dingle temperature ( $T_D$ ) for all the bands using the LK formula [Eq. (1)] (Fig. S6 in Supplemental Material[14]) and listed the values in Tab. 1. Taking the  $\gamma$ -band as an example, we have calculated several physical quantities characterizing the Fermi surface. As  $F_{\gamma} = 102$  T, using Onsager's relation  $F = \hbar/(2e)k_F^2$ ; the Fermi momentum is  $k_F = 0.056 \text{ \AA}^{-1}$ . The corresponding Fermi surface area ( $S_F$ ) is  $\pi k_F^2 = 0.973 \text{ \AA}^2$ . Using the linear dispersion relation in 2D,  $v_F = \hbar k_F/m^*$ , we have estimated the Fermi velocity  $v_F = 1.86 \times 10^5 \text{ ms}^{-1}$ . Using the value of  $T_D = 4.6$  K, the surface carrier life time  $\tau = \hbar/2\pi k_B T_D$  is estimated to be  $\tau_s = 2.630 \times 10^{-13}$  s. Similarly, other physical parameters like the mean free path  $l_{2D} = v_F \tau_s$  and mobility  $\mu = e\tau_s/m^*$  are estimated to be 48.815 nm and  $0.133 \text{ m}^2V^{-1}s^{-1}$ , respectively. There are no reports on AV<sub>3</sub>Sb<sub>5</sub> for comparison of these Fermi surface parameters, however, they are comparable with other topological systems[19, 27, 28]. Following the same procedure, we have determined those quantities for the remaining bands and tabulated them in Tab.1. Here, we have used the powerful magnetic fields up to 35 T to probe the Fermi surface properties of CsV<sub>3</sub>Sb<sub>5</sub>. As described earlier, the minimum fields of 15 T are needed to observe the dHvA oscillations. As the upper critical fields ( $H_{c2}$ )[29] for CsV<sub>3</sub>Sb<sub>5</sub> are  $H_{c2}$  (out-of-plane) = 0.8 T and  $H_{c2}$  (in-plane) = 7.2 T, the Fermi surface properties discussed here represent it at its normal state.

As we mentioned above, we have observed seven distinct frequencies in our dHvA oscillations and four of them are high frequencies (above 500 T) which are not

ported in the published data[10] yet. To further confirm the presence of high frequencies in CsV<sub>3</sub>Sb<sub>5</sub>, we have carried out additional measurements using the tunnel diode oscillation (TDO) technique. This unique technique has been used successfully to investigate the Fermi surface properties of topological materials in the past[30, 31]. Figure 5(a) shows the field dependence of the resonant frequency ( $\delta f_{TDO}$ ) with applied fields up to 35 T at 0.32 K and  $\theta = 0^\circ$ . As seen in the  $\delta f_{TDO}$  vs  $H$  plot, there is a clear indication of quantum oscillations above 10 T with several periods. This is further confirmed in the background subtracted data as shown in Fig. 5(b) and inset. To determine the frequencies of the oscillations, we have carried out a Fourier transform of the data which is displayed in (c) and (d). For comparison, we have also included the frequencies obtained from the magnetic torque data at  $\theta = 0^\circ$  in (c) and (d). As seen in Fig. 5(c) and (d), the frequency spectra obtained from these methods are comparable to one another. Note that there are ten distinct frequencies in the TDO frequency spectrum:  $F_1 = 22$  T,  $F_2 = 32$  T,  $F_3 = 72$  T,  $F_4 = 95$  T,  $F_5 = 170$  T,  $F_6 = 216$  T,  $F_7 = 728$  T,  $F_8 = 789$  T,  $F_9 = 1400$  T, and  $F_{10} = 1751$  T. Some of these frequencies (especially lower frequencies below 500 T) were also observed in previous reports[10, 12, 13], and their values are comparable to one another. We noticed that there are a few additional frequencies in TDO data which are not clearly defined in our torque measurements. This could be due to different sensitivities of these measurement techniques. Our TDO data further confirms that there exist four higher frequencies with values above 500T in CsV<sub>3</sub>Sb<sub>5</sub>. The TDO studies on CsV<sub>3</sub>Sb<sub>5</sub> are still in progress, and the detailed results will be reported elsewhere.

#### IV. SUMMARY

This work presents the normal state Fermi surface properties of the kagome superconductor CsV<sub>3</sub>Sb<sub>5</sub> using torque magnetometry with applied fields as high as 35 T. The torque signal clearly shows dHvA oscillations with seven distinct frequencies ranging from  $\sim 18$  T to 2135 T. Four frequencies have values above 500 T, which were not observed in the previous publication[10]. The presence of higher-frequencies in our data is confirmed

by carrying out further high-field measurements using the tunnel diode oscillator (TDO) technique. From the angle dependence of the dHvA oscillations and the Berry phase calculations, we have proved the non-trivial topology of the Fermi surface corresponding to these frequencies in CsV<sub>3</sub>Sb<sub>5</sub>. Several physical quantities characterizing the Fermi surfaces of CsV<sub>3</sub>Sb<sub>5</sub> are calculated using the Lifshitz-Kosevich formula and listed in a table. Although there are some recent Fermi surface studies in CsV<sub>3</sub>Sb<sub>5</sub> using Shubnikov-de Haas (SdH) oscillations, this work provides detailed angle dependence, temperature dependence, and Berry phase analyses using dHvA oscillations which helps to better understand the Fermi surface properties and its topological nature in CsV<sub>3</sub>Sb<sub>5</sub>.

*Note added.* During the preparation of this manuscript, we became aware of works by B. R. Ortiz et al.[12] and Y. Fu et al.[13] reporting the observation of high frequencies above 500 T in CsV<sub>3</sub>Sb<sub>5</sub> using the Shubnikov-de Haas (SdH) oscillations. Y. Fu et al.[13] reported four distinct frequencies below 1000 T, whereas B. R. Ortiz et al.[12] observed nine distinct frequencies up to 2000 T. In their works, the higher frequencies are suppressed quickly at higher angles ( $\theta > 20^\circ$ ); whereas those frequencies are clearly resolved up to  $\theta = 60^\circ$  enabling us to carry out angle dependence measurements to confirm the dimensionality of the Fermi surface.

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