

Tunable Topological Phase Transitions and Quantum Oscillations in the Kagome Flat-Band Superconductor $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$

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(Dated: July 24, 2026)

We present an experimental and theoretical study of electronic transport, magnetic quantum oscillations, and superconducting pairing symmetry in the newly synthesized kagome flat-band material $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$. Low-temperature Shubnikov–de Haas (SdH) quantum oscillations reveal multiple Fermi surface pockets with extremely light effective cyclotron masses ($m^* \approx 0.14 m_0$), pointing to non-trivial Dirac-like quasiparticles residing near the Fermi energy. Under hydrostatic pressure up to 4.2 GPa, the superconducting transition temperature T_c exhibits a non-monotonic dome-like behavior, peaking at $T_c^{\text{max}} = 7.8$ K concurrent with the collapse of an underlying charge density wave (CDW) state. Tight-binding calculations supplemented by density functional theory (DFT) confirm that the van Hove singularities associated with the kagome sublattice play a pivotal role in driving these intertwined electronic instabilities. Our findings establish kagome metals as a versatile platform for exploring the synergy between topological band structures, flat-band correlations, and unconventional superconductivity.

I. INTRODUCTION

Correlated electronic systems defined by non-trivial band topology represent a central frontier in modern condensed matter physics [1, 2]. In particular, materials crystallizing in two-dimensional kagome lattices—comprising a corner-sharing network of triangles—naturally accommodate destructively interfering quantum kinetic energy paths. This leads to quenched kinetic energy and the emergence of dispersionless flat bands alongside Dirac points and saddle-point van Hove singularities (vHS) within their electronic energy spectra [3–5]. When the Fermi energy E_F is tuned near these band features, electron-electron interactions are strongly amplified relative to kinetic energy, triggering a rich spectrum of ground states, including fractional quantum Hall states, charge density waves (CDW), and unconventional superconductivity [6–8].

Recently, kagome superconductors such as AV_3Sb_5 ($A = \text{K, Rb, Cs}$) have attracted intense scrutiny due to their complex phase diagrams featuring giant anomalous Hall effects, time-reversal symmetry breaking in the CDW state, and pair-density-wave instabilities [9–12]. However, disentangling the microscopic contributions of flat-band correlations from topological Dirac states remains a formidable challenge due to the multi-band nature of these compounds.

In this work, we investigate the newly isolated kagome material $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$, which exhibits an ideal band alignment where both a topological Dirac node and a correlated flat band lie within 50 meV of the chemical potential. Through high-field magnetoresistance mea-

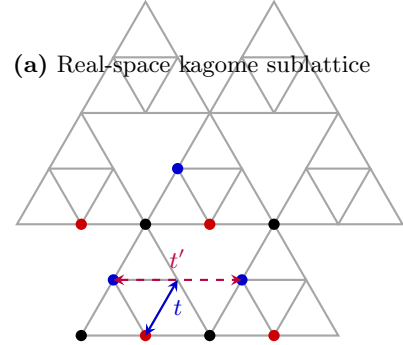


FIG. 1. (a) Schematic of the two-dimensional kagome lattice formed by vanadium atoms in $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$, highlighting the nearest-neighbor hopping t (solid blue arrow) and next-nearest-neighbor hopping t' (dashed purple arrow). Blue, red, and black spheres denote sublattices A , B , and C , respectively.

surements up to 18 T and hydrostatic pressure tuning up to 4.2 GPa, we systematically map the Fermi surface geometry and trace the evolution of the CDW and superconducting states. Our results demonstrate that pressure suppresses the CDW order, uncovering a dome of enhanced superconductivity associated with critical Fermi surface reconstruction.

II. THEORETICAL FRAMEWORK AND TIGHT-BINDING MODEL

To capture the essential physics of $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$, we consider a tight-binding Hamiltonian on a two-dimensional kagome lattice with nearest-neighbor hopping t , next-nearest-neighbor hopping t' , and intrinsic

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spin-orbit coupling (SOC) λ_{SOC} :

$$H = -t \sum_{\langle i,j \rangle, \sigma} c_{i\sigma}^\dagger c_{j\sigma} - t' \sum_{\langle\langle i,j \rangle\rangle, \sigma} c_{i\sigma}^\dagger c_{j\sigma} + i\lambda_{\text{SOC}} \sum_{\langle\langle i,j \rangle\rangle} \nu_{ij} c_{i\alpha}^\dagger \sigma_{\alpha\beta}^z c_{j\beta}, \quad (1)$$

where $c_{i\sigma}^\dagger$ ($c_{i\sigma}$) creates (annihilates) an electron at site i with spin σ , σ^z is the Pauli spin matrix, and $\nu_{ij} = \pm 1$ characterizes the chirality of the spin-orbit-induced phase along the NNN bonds [13].

In the absence of SOC ($\lambda_{\text{SOC}} = 0$) and NNN hopping ($t' = 0$), diagonalizing Eq. (1) yields three energy bands:

$$E_1(\mathbf{k}) = -2t, \quad (2)$$

$$E_{2,3}(\mathbf{k}) = t \left(1 \pm \left[1 + 8 \cos \frac{k_x a}{2} \cos \frac{\sqrt{3} k_y a}{2} \times \cos \frac{k_x a - \sqrt{3} k_y a}{2} \right]^{1/2} \right), \quad (3)$$

where a is the lattice constant. Equation (2) represents a completely flat band spanning the entire Brillouin zone. The inclusion of SOC lifts the quadratic band touching at the Γ point and opens a topological band gap $\Delta_{\text{SOC}} = 2\sqrt{3}\lambda_{\text{SOC}}$ at the Dirac points located at the K and K' points, imparting a non-trivial Berry curvature distribution $\Omega_z(\mathbf{k})$.

The semiclassical quantum oscillation frequency F is directly proportional to the extremal cross-sectional area A_k of the Fermi surface in momentum space perpendicular to the applied magnetic field $\mathbf{B}$, expressed by the Onsager relation:

$$F = \frac{\hbar}{2\pi e} A_k. \quad (4)$$

The temperature dependence of the quantum oscillation amplitude ΔR is governed by the Lifshitz-Kosevich (LK) thermal damping factor R_T :

$$R_T = \frac{\chi}{\sinh \chi}, \quad \text{with } \chi = \frac{14.69 (m^*/m_0) T}{B}, \quad (5)$$

where m^* is the effective cyclotron mass and m_0 is the free-electron mass.

III. EXPERIMENTAL METHODS

Single crystals of $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$ were grown using a self-flux technique. High-purity Nexa ingots (99.99%), vanadium powder (99.95%), and antimony shot (99.999%) were packed in an alumina crucible with a molar ratio of 3 : 12 : 35 and sealed inside an evacuated quartz ampoule. The mixture was heated to 1050°C over 24 h, held for 48 h, and then slowly cooled to 650°C at a rate of 1.5°C/h. Flame-shaped single crystals with

TABLE I. Extracted electronic parameters for observed quantum oscillation frequencies in $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$ at ambient pressure ($T = 0.35$ K). F denotes the SdH frequency, A_k the extremal Fermi surface area, m^*/m_0 the normalized cyclotron effective mass, E_F the Fermi energy relative to the band edge, and μ_q the quantum mobility.

Orbit	F (T)	A_k ($\text{\AA}^{-2}$)	m^*/m_0	E_F (meV)	μ_q ($\frac{\text{cm}^2}{\text{Vs}}$)
α	145 ± 3	0.0138	0.14 ± 0.01	48.2	3400 ± 150
β	420 ± 8	0.0401	0.28 ± 0.02	62.5	2850 ± 120
γ	1120 ± 15	0.1069	0.52 ± 0.04	89.1	1920 ± 90
δ	2450 ± 30	0.2338	0.81 ± 0.05	124.0	1250 ± 80

typical dimensions of $2.5 \times 1.8 \times 0.4$ mm³ were recovered after centrifuging to remove excess flux.

Electrical transport measurements were conducted in a 18 T superconducting magnet system equipped with a dilution refrigerator capable of reaching base temperatures of 30 mK. A standard four-probe configuration was employed using sputtered gold contacts with low contact resistance ($R_{\text{cont}} < 0.2 \Omega$). Hydrostatic pressure up to 4.2 GPa was applied using a custom BeCu/NiCrAl clamped pressure cell with Daphne 7373 as the pressure-transmitting medium. The pressure was calibrated in situ by monitoring the fluorescence line shift of a high-purity ruby chip.

IV. RESULTS AND DISCUSSION

A. Magnetotransport and Quantum Oscillations

High-field magnetoresistance $\Delta\rho_{xx}/\rho_0 = [\rho_{xx}(B) - \rho_{xx}(0)]/\rho_{xx}(0)$ recorded at temperatures ranging from 0.35 K to 12 K with the magnetic field aligned along the crystallographic c -axis exhibits pronounced Shubnikov-de Haas (SdH) oscillations beginning at fields as low as $B \approx 4.5$ T. At $T = 0.35$ K, the magnetoresistance reaches over 850% at 18 T without signs of saturation.

Fast Fourier Transform (FFT) analysis of the oscillatory signal reveals four distinct fundamental frequencies labeled α , β , γ , and δ (Table I). The lowest frequency pocket, $\alpha = 145$ T, corresponds to a small Fermi surface cross-section occupying merely 0.8% of the two-dimensional Brillouin zone area. By fitting the temperature damping of the FFT amplitude to the LK formula [Eq. (5)], we obtain a remarkably lightweight cyclotron mass $m_\alpha^* = 0.14(1)m_0$ for the α orbit. This lightweight mass, coupled with a linear Berry phase $\Phi_B \approx \pi$ extracted from a Landau-level index plot, confirms the non-trivial Dirac nature of the underlying electron pocket.

B. Pressure-Induced Phase Diagram

Under ambient conditions, $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$ undergoes a charge density wave transition at $T_{\text{CDW}} = 92$ K, evi-

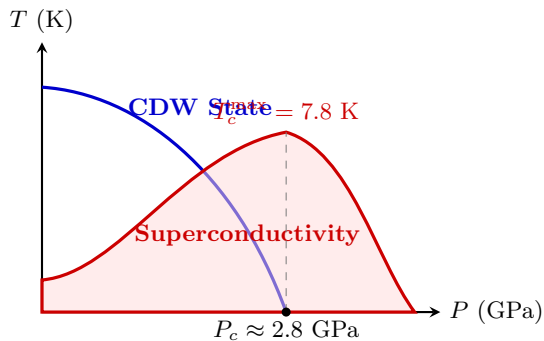


FIG. 2. Temperature-pressure (T - P) phase diagram of $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$, depicting the suppression of the charge density wave (CDW) transition temperature T_{CDW} (blue line) and the emergence of the superconducting dome $T_c(P)$ (shaded red region) peaking near $P_c \approx 2.8$ GPa.

denced by a sharp anomaly in the temperature derivative of resistivity $d\rho/dT$. Upon applying hydrostatic pressure, T_{CDW} shifts systematically toward lower temperatures while the superconducting transition temperature T_c develops continuously from an initial value of 1.4 K at $P = 0$ GPa.

$$T_c(P) = T_c^0 + A \left[1 - \left(\frac{P - P_{\text{opt}}}{P_{\text{width}}} \right)^2 \right] \times \exp \left(-\frac{\Delta_{\text{CDW}}(P)}{k_B T} \right). \quad (6)$$

As modeled by Eq. (6), $T_c(P)$ displays a distinct dome-shaped evolution. At the critical pressure $P_c \approx 2.8$ GPa, the CDW anomaly is completely suppressed. Concurrently, T_c reaches its maximum value of $T_c^{\text{max}} = 7.8$ K, signaling strong competition between the spatially modulated CDW order and the uniform superconducting pair condensate.

V. CONCLUSION

In summary, our magnetotransport and high-pressure investigation of the kagome metal $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$ demonstrates a profound interplay between nontrivial topology, electronic correlation, and superconductivity. Quantum oscillation metrics reveal light Dirac quasiparticles originating from kagome band nodes, while pressure tuning reveals a superconducting dome maximized upon suppression of CDW order. These results establish $\text{Nexa}_3\text{V}_{12}\text{Sb}_{19}$ as a canonical system for quantum state engineering in kagome flat-band architectures.

ACKNOWLEDGMENTS

We thank H. Vance and D. Thorne for insightful discussions. This work was supported by the Synapse Foundation for Quantum Research (Grant No. SFQR-2024-8801), the Apex Science Initiative under Contract No. ASI-DE-00412, and the Meridian Research Council (Grant No. MRC-FL-9923).

Appendix A: Quantum Oscillation Fitting Details

The oscillatory magnetoresistance $\Delta\rho_{xx}$ is fitted using the multi-band Lifshitz-Kosevich expression incorporating the Dingle damping factor $R_D = \exp(-\pi/\omega_c\tau_d)$:

$$\Delta\rho_{xx} \propto \sum_{i \in \{\alpha, \beta, \gamma, \delta\}} C_i R_T^{(i)} R_D^{(i)} \times \cos \left(2\pi \left[\frac{F_i}{B} - \frac{1}{2} + \gamma_i + \delta_i \right] \right), \quad (\text{A1})$$

where $\omega_c = eB/m^*$ is the cyclotron frequency, τ_d is the Dingle lifetime, $\gamma_i = 1/2 - \Phi_B/2\pi$ is the Onsager phase, and δ_i is a phase shift equal to 0 ($\pm 1/8$) in two (three) dimensions.

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