

Probing the Fermi surface with quantum oscillation measurements in the Dirac semimetal TaNiTe₅

Maximilian Daschner,^{1,2,*} Bruno Gudac,³ Mario Novak³,,³ Cheng Liu³,,¹ F. Malte Grosche³,,¹ and Ivan Kokanović^{1,3,†}

¹*Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom*

²*Fakultät für Physik, Ludwig-Maximilians-Universität, München, Germany*

³*Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia*



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We report a detailed investigation of the Fermi surface in the layered Dirac semimetal TaNiTe₅. We probed the magnetization, magnetic torque, and magnetoresistance in high-quality single crystals. Pronounced Shubnikov–de Haas and de Haas–van Alphen oscillations are observed in magnetic fields above 3 T and at temperatures of up to 22 K. Multiple fundamental frequencies and light effective quasiparticle masses are obtained by fast Fourier transformation (FFT) and Lifshitz-Kosevich formula fits. The high resolution of the low-temperature FFT spectra allows us to investigate individual peaks in detail for the magnetic fields applied along all three crystallographic axes and the planes in between. Our investigation can confirm the density functional theory calculated band structure and its corresponding Fermi surface.

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I. INTRODUCTION

Topological semimetals represent a new class of quantum materials hosting Dirac [1–4] or Weyl fermions [5–13], in which the valence and conduction bands touch and form nodal points. Furthermore, Dirac nodal lines in which Dirac cones form lines in reciprocal space lead to the more general concept of nodal-line semimetals (NLSMs) [14–20]. NLSMs usually occur in three-dimensional materials where they hold more symmetries such as mirror and nonsymmorphic symmetries that protect the Dirac band touching structures against spin-orbit coupling (SOC) [16,19]. Evidence for robust Dirac nodal lines in (quasi-)one-dimensional materials has been missing until recently when they were reported in the exfoliable, in-plane anisotropic nonmagnetic semimetal TaNiTe₅ by combining angle-resolved photoemission spectroscopy (ARPES) and density functional theory (DFT) calculations [21]. Quantum oscillation studies have reported evidence for Fermi surface pockets with nontrivial Berry phase in TaNiTe₅ and highly anisotropic properties were shown in magnetization and transport measurements [22–24]. These previous studies were performed for magnetic fields applied parallel to the crystallographic *a* and *b* axes. However, a systematic study of quantum oscillations for magnetic fields parallel to the crystallographic *c* axis or in any of the planes perpendicular to the *a* or *b* axes remains absent. Here, we report a detailed investigation of the Fermi surface in TaNiTe₅ single crystals through magnetization, magnetic torque, and magnetoresistance measurements for magnetic

fields of up to 14 T along all three principal axes and a rotational study in all three planes. We observed pronounced de Haas–van Alphen (dHvA) and Shubnikov–de Haas (SdH) oscillations with multiple frequencies at temperatures below 22 K and magnetic fields above 3 T. The observed quantum oscillation frequencies in these crystals closely agree with each other, evidencing the same electronic structure. Changing the magnetic field direction results in a clear change of the oscillation frequencies, indicating anisotropic Fermi surface pockets. By analyzing the SdH and dHvA quantum oscillations, multiple fundamental frequencies, small effective masses, low Dingle temperatures, and high mobility of charge carriers are obtained. The high resolution of the low-temperature fast Fourier transformation (FFT) spectra in the observed magnetization and magnetoresistance data allows us to investigate individual peaks in detail. Our results shed light on the electronic properties of the Dirac semimetal TaNiTe₅ and serve as a basis for the study of low-dimensional quantum materials and their topological properties.

II. EXPERIMENTAL METHODS

The TaNiTe₅ crystals were synthesized by the self-flux method [23,25]. The mixture at a molar ratio of Ta : Ni : Te = 1 : 1 : 10 was loaded into an alumina crucible and sealed inside a quartz tube in high vacuum. The mixture was then heated to 700 °C over the course of four days and slowly cooled to 500 °C within a week. The resulting single crystals have an orthorhombic layered structure with the space group *Cmcm* (no. 63) [25]. The structure features one-dimensional (1D) NiTe₂ chains along the crystallographic *a* axis, which form a quasi-2D layer by linking chains of Ta atoms along the *c* axis as can be seen in Fig. 1(a). The lattice constants are inferred from powder x-ray diffraction (XRD) data with *a* = 3.657 Å, *b* = 13.183 Å, and *c* = 15.119 Å. The peaks of the single-crystal XRD pattern showed no trace of an impurity phase, indicating high crystalline quality (see Appendix A).

*Contact author: maximilian.daschner@lmu.de

†Contact author: kivan@phy.hr

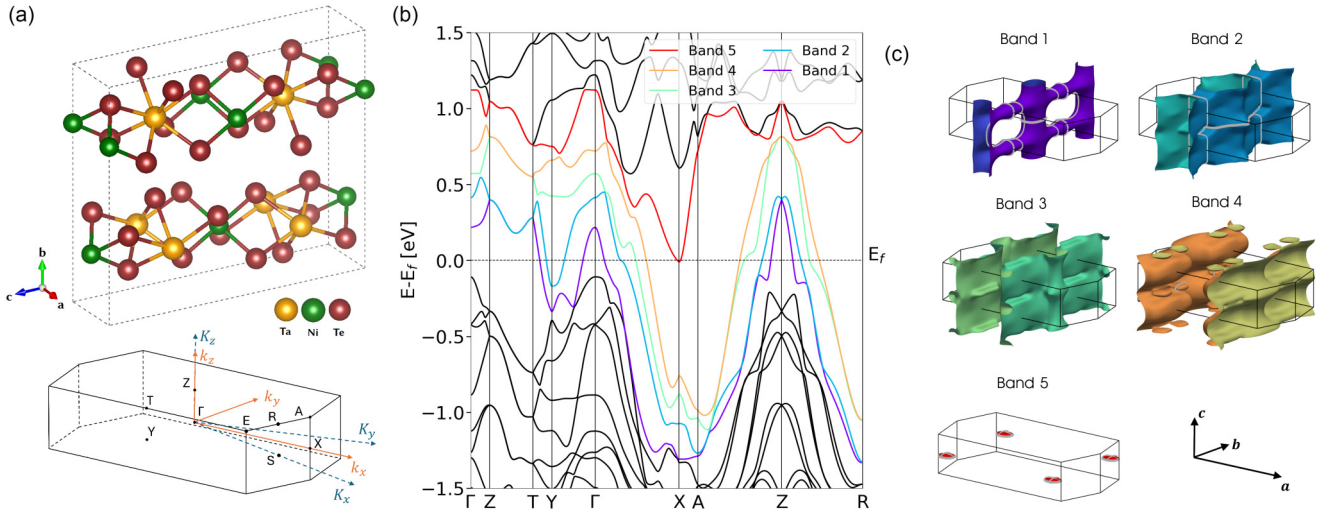


FIG. 1. (a) Unit cell and first Brillouin zone in TaNiTe₅. In the Brillouin zone, k_x , k_y , and k_z point in conventional unit cell vector directions which go through high-symmetry points X, Y, and Z and align with the crystallographic axes a , b , and c , respectively, while K_x , K_y , and K_z are the reciprocal lattice vectors that represent the periodicity of the Brillouin zone. (b) Band structure including spin-orbit coupling along high-symmetry lines. (c) Fermi sheets for TaNiTe₅ with the Fermi level shifted to lower energies by approximately 20 meV. Extremal orbits are shown for the magnetic field along a , b , and c as gray lines in the first Brillouin zone.

The crystals grow in the shape of flat needles along the a axis. Magnetization measurements in two crystals with masses of 25 mg and 27.4 mg were carried out using a 14 T Quantum Design Physical Property Measurement System (PPMS) with VSM option. The magnetoresistance was measured using standard ac lock-in techniques in a 9 T PPMS. We have also performed magnetic torque measurements on two crystals in magnetic fields of up to 9 T and 13 T for the angle-dependent measurement in the a - b plane and the b - c plane, respectively. These were carried out in the aforementioned 9 T PPMS and a customized 13 T Oxford Instruments cryostat. The crystals were mounted on home-made piezoresistive cantilevers and placed on a rotating platform.

III. AB INITIO CALCULATIONS

To gain insights into the electronic structure of TaNiTe₅, we have performed density functional theory (DFT) calculations using the full-potential linearized augmented plane wave method implemented in the WIEN2K package [26]. The PBE-GGA exchange-correlation functional [27] was chosen here. The atomic sphere radii (muffin-tin radii) were chosen as $R_{mt} = 2.5$ a.u. for the Ta and Ni atoms, and $R_{mt} = 2.43$ a.u. for all Te atoms. The plane-wave cutoff parameter was chosen as $R_{mt}K_{max} = 8$, where R_{mt} is the smallest atomic sphere radius in the unit cell and K_{max} is the magnitude of the largest k vector. Calculations were performed on a $59 \times 59 \times 13$ k -point mesh in the full Brillouin zone for the band structure calculations shown here. Figure 1(b) illustrates the resulting band structure including spin-orbit coupling (SOC) with its respective Fermi sheets shown in Fig. 1(c). The Fermi sheets for each band also include extremal areas for magnetic fields aligned with the three crystallographic axes a , b , or c .

From Fig. 1(b) it can be seen that linearly dispersing bands appear in pairs along the A - Z - R high-symmetry line, forming type-I Dirac cones in Z and type-II Dirac cones in R as the

bands maintain their spin degeneracy. Similar to the material family members TaXTe₅ ($X = \text{Pd, Pt}$), TaNiTe₅ also hosts a fourfold degenerate nodal line along Z - T , with linear dispersion along Γ - Z and T - Y . Symmetry considerations [1,28] performed in the literature for materials that crystallize in the symmetry group $Cmcm$ (63), e.g., TaNiTe₅ [21], TaPtTe₅ [29], LaNiGa₂ [30], and Th₂BC₂ [31], show protection of such nodal lines. Their energetic location is around 200 meV above the Fermi level, making it unlikely for them to influence our obtained experimental results [22,32,33].

IV. THEORY

In metals and semimetals, oscillations in various physical quantities in magnetic field are well described by the grand

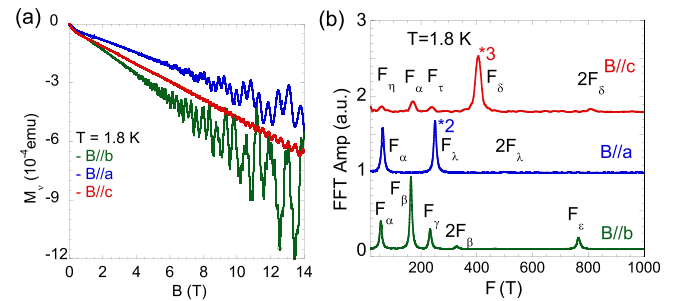


FIG. 2. (a) Magnetization of a layered TaNiTe₅ single crystal with a mass of 25.6 mg at a temperature of 1.8 K. The magnetic field is applied parallel to the crystallographic b , a , and c axes, respectively. The curves show an interpolation of data points with a few data points highlighted for $\mathbf{B} \parallel c$ (red circle), $\mathbf{B} \parallel a$ (blue square), and $\mathbf{B} \parallel b$ (green triangle). (b) FFT spectra of the dHvA oscillations in the isothermal magnetization data extracted after subtracting the diamagnetic backgrounds shown in (a). The FFT amplitudes of the spectra have been generated from the magnetization data between 4 T and 14 T and are shifted vertically for clarity.

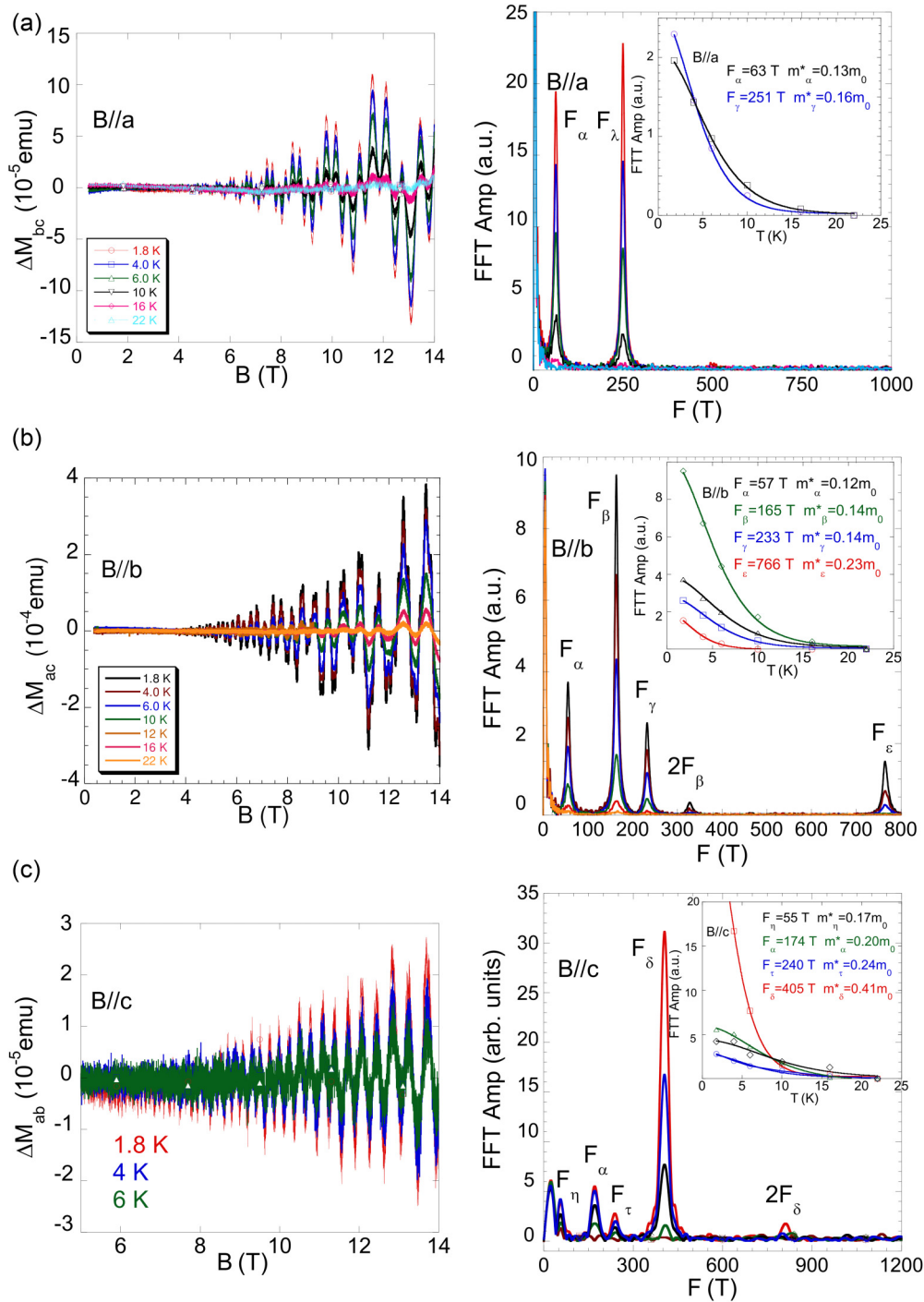


FIG. 3. Analysis of dHvA oscillations with (a) $\mathbf{B} \parallel a$, (b) $\mathbf{B} \parallel b$, and (c) $\mathbf{B} \parallel c$. Left: the oscillatory components of the isothermal magnetization ΔM after subtracting the diamagnetic background at various temperatures. Right: the corresponding FFT amplitude of the spectra has been generated from data between 4 T and 14 T. The inset shows the fits of the temperature damping factor R_T in the LK formula to the FFT amplitudes.

thermodynamical potential given by the Lifshitz-Kosevich (LK) formula [34]:

$$\Omega = \sum_i C_i B^{\frac{5}{2}} R_T R_D \cos \left[2\pi \left(\frac{F_i}{B} - \frac{1}{2} + \phi \right) \right], \quad (1)$$

where the sum is over all orbits i along a Fermi sheet and we assume only one harmonic for simplicity. B is the

magnetic field, C_i is a B -independent constant, F is the dHvA frequency of the oscillations, which can be related to the extremal area A of the individual pocket via the Onsager relation $F = A(\phi_0/2\pi^2)$, where ϕ_0 is the magnetic flux quantum [34], and m^* is the quasiparticle effective mass. We also include a phase shift $\phi = \phi_B/2\pi + \delta$, where ϕ_B is the Berry phase and δ is an additional phase shift depending on the dimensionality of the Fermi surfaces, i.e., $\delta = 0$ for 2D

TABLE I. Extracted properties from de Haas–van Alphen oscillations in the magnetization.

	F (T)	A_F ($\text{\AA}^{-2}$)	m^* (m_e)	T_D (K)	τ_q (10^{-14} s)	μ_q ($\text{m}^2/\text{V s}$)	l (nm)	ϕ (π)
B $\parallel$ b								
F_α	56.8(3)	0.00542(3)	0.12(1)	15.5(3)	7.8(2)	0.11(1)	31(3)	0.64(5)
F_β	164.7(3)	0.01572(3)	0.14(1)	12.6(3)	9.6(2)	0.121(9)	56(4)	1.14(4)
F_γ	233.1(3)	0.02225(3)	0.14(2)	12.5(5)	9.7(4)	0.12(2)	70(10)	0.98(3)
F_δ	766.0(5)	0.07312(5)	0.23(2)	12.3(5)	9.9(4)	0.076(7)	76(7)	0.81(4)
B $\parallel$ c								
F_η	55.3(3)	0.00528(3)	0.17(2)	28.6(3)	4.25(4)	0.044(5)	12(1)	
F_α	173.8(4)	0.01659(4)	0.20(2)	13.4(3)	9.1(2)	0.080(8)	38(4)	1.03(3)
F_τ	240.0(4)	0.02291(4)	0.24(3)	13.6(4)	8.9(3)	0.066(8)	37(5)	
F_δ	405.2(4)	0.03868(4)	0.41(2)	4.7(3)	26(2)	0.111(9)	81(7)	1.30(3)
B $\parallel$ a								
F_α	63.0(3)	0.00601(3)	0.13(1)	15.8(3)	7.7(1)	0.104(8)	30(2)	1.10(5)
F_λ	251.0(4)	0.02396(4)	0.16(1)	10.8(3)	11.3(3)	0.124(8)	71(5)	1.01(5)
B $\parallel$ $a \rightarrow$ B $\parallel$ c ($\theta = 15^\circ$)								
F_α	64.0(2)	0.00611(2)	0.19(1)	12.9(5)	9.4(4)	0.087(6)	25(2)	0.62(3)
F_λ	254.0(4)	0.02425(4)	0.24(1)	8.7(3)	14.0(5)	0.102(6)	59(3)	0.95(4)
B $\parallel$ $a \rightarrow$ B $\parallel$ c ($\theta = 35^\circ$)								
F_α	73.0(2)	0.00697(2)	0.18(1)	12.4(4)	9.8(3)	0.096(6)	30(2)	0.61(3)
F_λ	286.0(4)	0.02730(4)	0.26(1)	12.5(4)	9.7(3)	0.066(3)	40(2)	1.28(5)

Fermi surfaces and $\delta = \pm 1/8$ for 3D Fermi surfaces ($-1/8$ for the electronlike and $1/8$ for the holelike). $R_T = X/\sinh(X)$ with $X = 2\pi^2 k_B m^* T/(\hbar e B)$ is the temperature damping factor, while $R_D = \exp(-X T_D/T)$ is the Dingle damping factor which accounts for the finite particle lifetime.

The mean free path l can be approximated under the assumption of a spherical Fermi surface as

$$l = \frac{\sqrt{2e\hbar^3 F}}{2\pi m^* k_B T_D}, \quad (2)$$

while quantum relaxation time and quantum mobility are defined as $\tau_q = \hbar/(4\pi^2 k_B T_D)$ and $\mu_q = e\tau_q/m^*$, respectively.

Shubnikov–de Haas oscillations in the magnetoresistance are proportional to Eq. (1), while de Haas–van Alphen oscillations in the magnetization can be derived via $M_\parallel = -(\frac{d\Omega}{dB})$. Oscillations in the magnetic torque are then given by

$$\tau = \mathbf{M}_\perp \times \mathbf{B}, \quad (3)$$

where the perpendicular magnetization is given by

$$\mathbf{M}_\perp = -\frac{1}{F} \frac{dF}{d\theta} \cdot \mathbf{M}_\parallel. \quad (4)$$

Using this formalism, we will analyze the magnetization, magnetic torque, and magnetoresistance data obtained for TaNiTe₅ in what follows.

V. EXPERIMENTAL RESULTS

A. Magnetization

Figure 2(a) shows a series of magnetization measurements in TaNiTe₅ at a temperature of 1.8 K, with magnetic fields applied along the crystallographic a , b , and c axes.

TaNiTe₅ exhibits large dHvA quantum oscillations with multiple frequencies superimposed on different linear diamagnetic backgrounds. By changing the direction of the magnetic field from **B $\parallel$ b** to **B $\parallel$ a** , and to **B $\parallel$ c** , the oscillation components are gradually suppressed, illustrating the anisotropic electronic properties of this material with an anisotropic magnetic susceptibility ratio of $\chi_a : \chi_c : \chi_b = 3.3 : 4.5 : 6.3$ at 1.8 K.

In Fig. 2(b), we have performed a FFT analysis of the isothermal magnetization data shown in Fig. 2(a). Several clearly resolved peaks are visible for the magnetic field parallel to each crystallographic axis, which we label with greek letters. The observed frequencies (F) in the FFT spectra are related to the extremal area through the Onsager relation. Frequencies we found here are consistent with the literature [22–24].

The raw data for the magnetization measurements along all three crystallographic axes at different temperatures is given in Appendix B. The diamagnetic background in this data was subtracted with a polynomial and the resulting oscillatory part was fast Fourier transformed as illustrated in Fig. 3. From the FFT amplitudes, the effective mass m^* can be extracted using the temperature-damping term R_T as shown in the insets on the right. With the fitted effective mass as a known parameter, we have further fitted the oscillation pattern at 1.8 K to the LK formula, from which the Dingle temperature T_D , quantum mobility μ_q , and a phase shift ϕ of the Fermi pockets are extracted and listed in Table I. Only two orbits were considered in each fit at a time. After subtracting the corresponding oscillation pattern, we performed another two-band LK formula fit to the residual data (see Appendix C). Note that for **B $\parallel$ c** the amplitude was too low to obtain reliable values for the phase shift ϕ for F_η and F_τ . The fitted Dingle temperature T_D , the

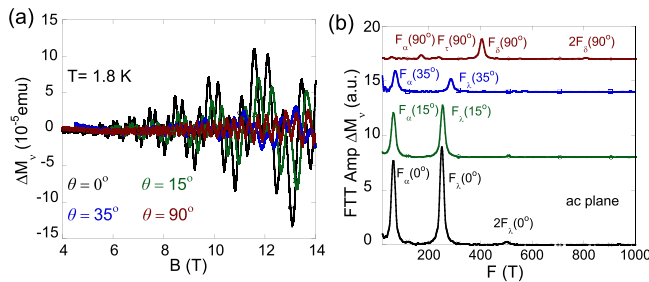


FIG. 4. (a) Magnetic field-dependent oscillatory components of the magnetization after subtracting the linear diamagnetic background at different angles in the a - c plane at $T = 1.8$ K. (b) The corresponding FFT spectra for different angles. The angle θ in the a - c plane is defined as the angle between the applied magnetic field and the a axis.

quantum relaxation time τ_q , and quantum mobility μ_q for all frequencies are also included in Table I.

To probe the morphology of the Fermi surface, we furthermore carried out angle-dependent quantum oscillation measurements in the magnetization with the applied magnetic field in the crystallographic a - c plane. The background subtracted raw data for four angles in that plane including its respective FFT is shown in Fig. 4. With increasing angle θ from 0° to 90° , the oscillation components are suppressed gradually. In the a - c plane, it can be seen from Fig. 5 that, with increasing the angle θ , the oscillation frequency F_α changes only slightly from 63 T ($\theta = 0^\circ$) to 73 T ($\theta = 35^\circ$), before increasing steeply to 173.8 T at $\theta = 90^\circ$, indicating a 3D elliptical Fermi pocket. This motivates fitting the angle dependence of the F_α pocket with the 3D ellipsoid model (thin red line) described in [35]. On the other hand, the frequency F_λ increases from 251 T ($\theta = 0^\circ$) to 286 T ($\theta = 35^\circ$) and disappears for the angles larger than ($\theta = 35^\circ$). We also include the results from DFT calculations in Fig. 5, which seem to agree well with the experimental findings after shifting the

Fermi energy by 20 meV. Particularly bands 243 and 249 (see Fig. 1) can explain the presence of the branches F_λ and F_α , respectively, while band 241 seems to overestimate F_δ . The frequencies $F_\tau = 240$ T and $F_\eta = 55.3$ T for $\mathbf{B} \parallel c$ are two unique frequencies. With the strong anisotropy of the crystal, the oscillatory signal is the weakest along the c direction and more measurements are necessary to conclusively confirm the existence of these two additional frequencies. Effective masses and other quantities were extracted for data points in the a - c plane and are included in Table I.

For magnetic fields aligned with the crystallographic b axis, we find excellent agreement between the magnetization data and DFT calculations.

B. Magnetic torque

To obtain a better understanding of the morphology of the Fermi surface, we carried out angle-dependent quantum oscillation measurements in the magnetic torque at a constant temperature of 1.8 K with the magnetic field in the a - b plane up to 9 T and in the b - c plane up to 13 T. An analysis is shown in Appendix D and the results are summarized Fig. 5. Again, the oscillation frequency F_α can be fitted well with the 3D ellipsoid model. The lower and upper branches arising from band 241 in the DFT calculations can be observed in the magnetic torque measurements as well as the higher frequency branches (> 800 T). Overall we find good agreement between the *ab initio* results and our measurement data. The branch arising from band 241 close to the c axis again appears to overestimate the measurement data.

Comparing these results to the rotation study in magnetic torque in the a - b plane performed by Chen *et al.* [23], we have observed agreement for the low frequency branch F_α (band 249), both in magnitude and the angle dependence. Chen *et al.* [23] also report oscillation data for the electron branch from band 243 and lower hole branch from band 241, although they mistakenly conclude that these frequencies must arise from the same Fermi surface. The upper hole branch from

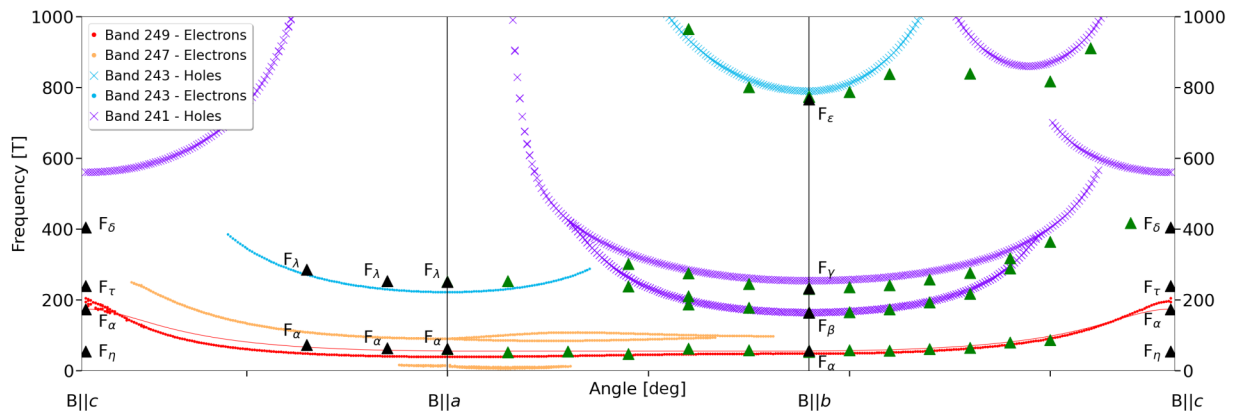


FIG. 5. Angular dependence of the oscillation frequencies. The F_α branch was fitted with the ellipsoid model shown as a thin red line. DFT calculations are included as described in the legend. Data by magnetization and magnetic torque are included as black and green triangles, respectively. Ticks correspond to 50° .

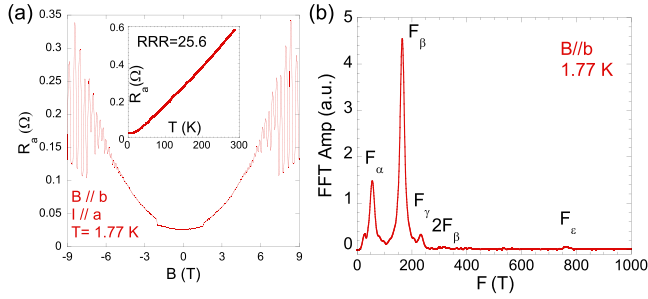


FIG. 6. (a) Magnetic field dependent resistance R_a with the current applied along the a axis and the magnetic field parallel to the b axis. The inset shows the temperature dependence of the resistance R_a at 0 T. (b) The FFT spectrum of ΔR_a generated in the magnetic field range from 3 to 9 T.

band 241 was not reported at all. Furthermore, Chen *et al.* [23] also report the hole branch from band 243 and an additional branch with similar angular dependence with a 150 T larger frequency. However, both results disagree with the authors' own Shubnikov–de Haas study, which finds only one instead of two frequencies at a value more consistent with our measurements.

C. Magnetoresistance

Figure 6(a) shows the magnetoresistance data with the magnetic field parallel to the b axis and the applied current parallel to the a axis. The oscillations in the magnetoresistance shown here are significantly more pronounced than what has been reported in recent works [22,23], in which quantum oscillations in the magnetoresistance of TaNiTe₅ were only observed at magnetic fields of up to 50 T. The strong quantum oscillations shown here indicate a possible new topological phenomenon; however, a model based on classical phenomena can fully explain the origin of this amplification of quantum oscillations as described in more detail in [36].

The inset to Fig. 6(a) shows the temperature dependence of the resistance R_a displaying a typical metallic behavior. The resistance follows a T -linear dependence from 280 K to 50 K and then a crossover to a quadratic T dependence indicating Fermi liquid behavior below 50 K. The residual resistance ratio is measured as $RRR = 25.6$. Moreover, the quasi-1D transport behavior with a resistance ratio of $\rho_a : \rho_c = 1 : 4$

at 2 K has been obtained and is consistent with previous reports [22,23]. Using this data, we performed a fast Fourier transform in the magnetic field range between 3 T and 9 T as shown in Fig. 6(b).

Similar to the magnetization data, magnetoresistance data in the temperature range 1.77–20 K allows us to extract the effective mass and other parameters (see Appendix F). Given m^* , the Dingle temperature T_D , quantum mobility μ_q , and the phase shift ϕ_B of the Fermi pockets are extracted at $T = 1.77$ K and summarized in Table II. The resolution of the γ and ϵ pockets is too low to extract most parameters other than the frequencies and the effective mass for the γ pocket. These results are consistent with those measured in the magnetization and the magnetic torque.

VI. CONCLUSIONS

We performed high-resolution measurements of de Haas–van Alphen and Shubnikov–de Haas quantum oscillations in layered TaNiTe₅ along all three crystallographic axes and the planes in between. The obtained fundamental frequencies in the FFT spectra resulting from dHvA measurements are consistent with those found in SdH measurements when the magnetic field is applied parallel to the b axis. Furthermore, quantum oscillation measurements in the magnetization, magnetic torque, and the magnetoresistance are consistent with previously reported values in the literature and density functional theory calculations performed here. Our rotation studies allow us to map out the morphology of the Fermi surface in this material and we discovered unique fundamental frequencies.

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TABLE II. Extracted properties from Shubnikov–de Haas oscillations in the resistivity with $\mathbf{B} \parallel b$ and $\mathbf{I} \parallel a$.

	F (T)	A_F ($\text{\AA}^{-2}$)	m^* (m_e)	T_D (K)	τ_q (10^{-14} s)	μ_q (m^2/Vs)	l (nm)	ϕ (π)
F_α	53.0(3)	0.00506(3)	0.14(2)	12.9(4)	9.4(3)	0.12(2)	31(5)	1.03(3)
F_β	163.0(4)	0.01556(4)	0.23(1)	14.7(3)	8.3(2)	0.063(3)	29(1)	1.05(4)
F_γ	233(3)	0.0222(3)	0.23(3)					
F_ϵ	766(5)							

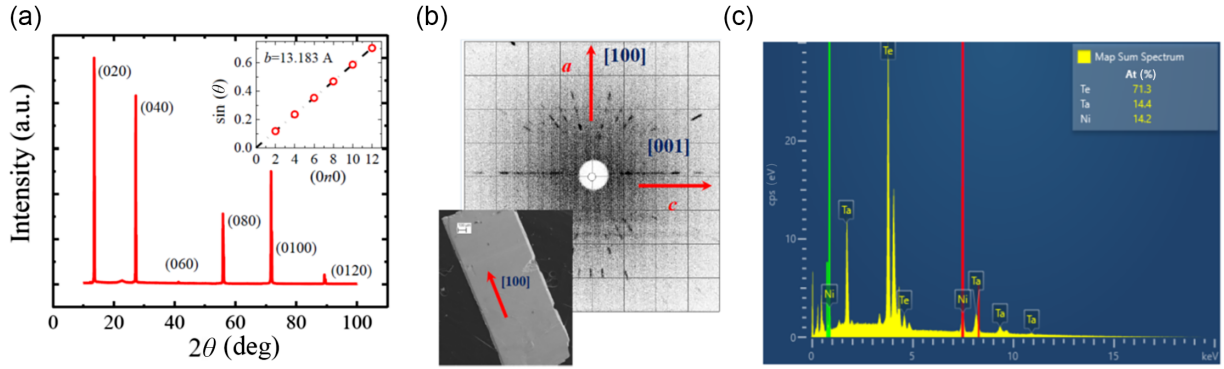


FIG. 7. (a) Single crystal x-ray diffraction pattern. The inset shows the extracted value of the lattice parameter b . The sharp diffraction peaks indicate the high quality of our crystals. (b) Laue x-ray diffraction pattern, where the inset shows an optical image of a typical crystal. (c) The energy-dispersive x-ray spectrum.

APPENDIX A: METHODS

Figure 7 shows the characterization of a TaNiTe_5 single crystal. X-ray diffraction and energy-dispersive x-ray spectroscopy indicate highly crystalline samples.

APPENDIX B: RAW DATA FOR MAGNETIZATION MEASUREMENTS

Figure 8 shows magnetization measurements of a TaNiTe_5 single crystal for fields of up to 14 T at various temperatures. The anisotropy of the crystal is reflected in the amplitude of the quantum oscillations.

APPENDIX C: ANALYSIS OF MAGNETIZATION MEASUREMENTS

Analysis of the dHvA data is illustrated in Figs. 9 and 10. The corresponding fitting method for each data set is explained in the figure captions.

APPENDIX D: RAW DATA FOR MAGNETIC TORQUE MEASUREMENTS

Raw magnetic torque data for TaNiTe_5 single crystals are illustrated in Fig. 11 with the magnetic field in the a - b and b - c plane. The corresponding fast Fourier transforms for each angle are given in Figs. 12 and 13, respectively.

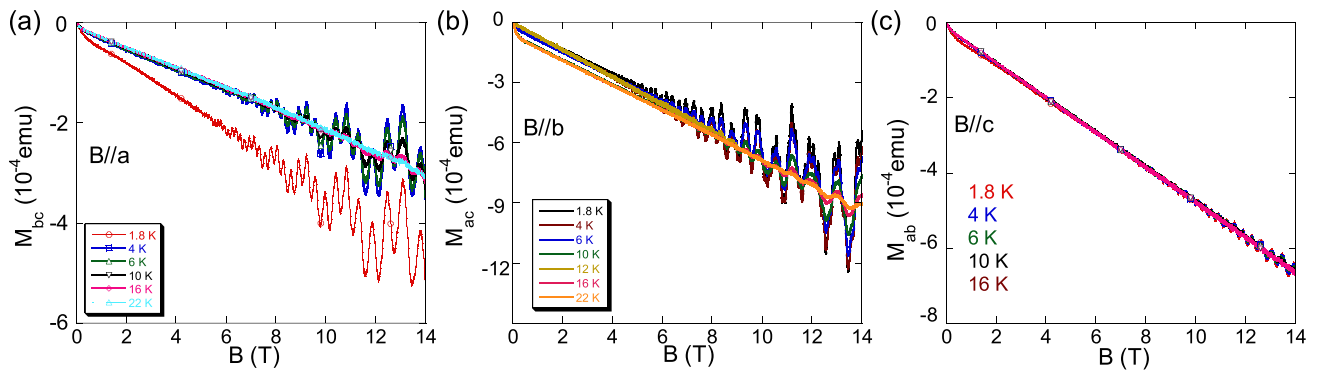


FIG. 8. Magnetization for magnetic fields of up to 14 T at various temperatures with the magnetic field applied parallel to the crystallographic (a) a axis, (b) b axis, and (c) c axis.

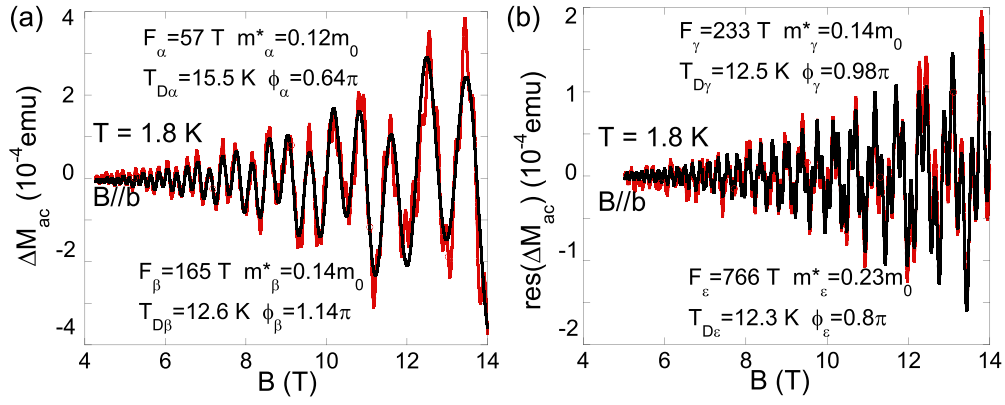


FIG. 9. (a) Oscillatory component of the isothermal magnetization ΔM after subtracting a diamagnetic background. The magnetic field is applied parallel to the crystallographic b axis. The black lines show the fit of the oscillation pattern assuming two bands. (b) Two-band LK formula fit to the residual after subtracting the first two-band fit from the data in (a). This result implies that the raw data can best be fitted with a four-band LK formula.

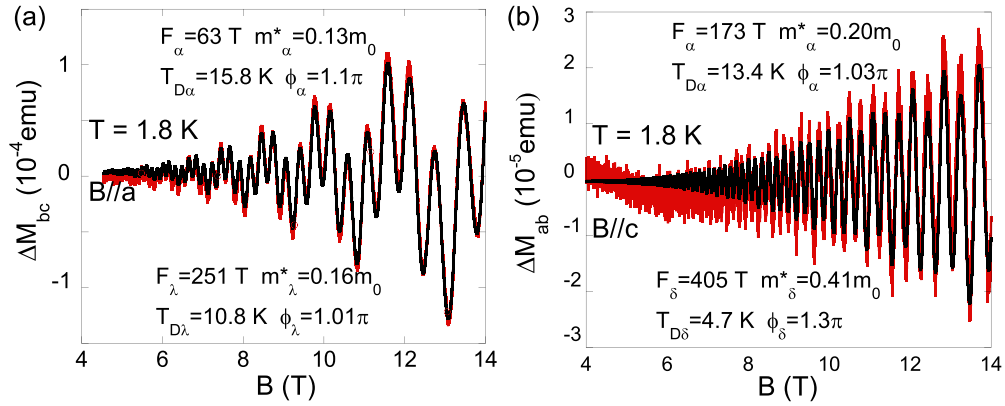


FIG. 10. Oscillatory components of the isothermal magnetization ΔM after subtracting the diamagnetic background. The magnetic field is applied parallel to the crystallographic (a) a and (b) c axis. The black lines show the fit of the oscillation pattern assuming two bands. In (b) another two-band fit was performed after subtracting the first two-band fit from the raw data similar to Fig. 9 (not shown here) to obtain values for F_τ and F_η . However, the resolution was too low to extract meaningful information about the phase shift.

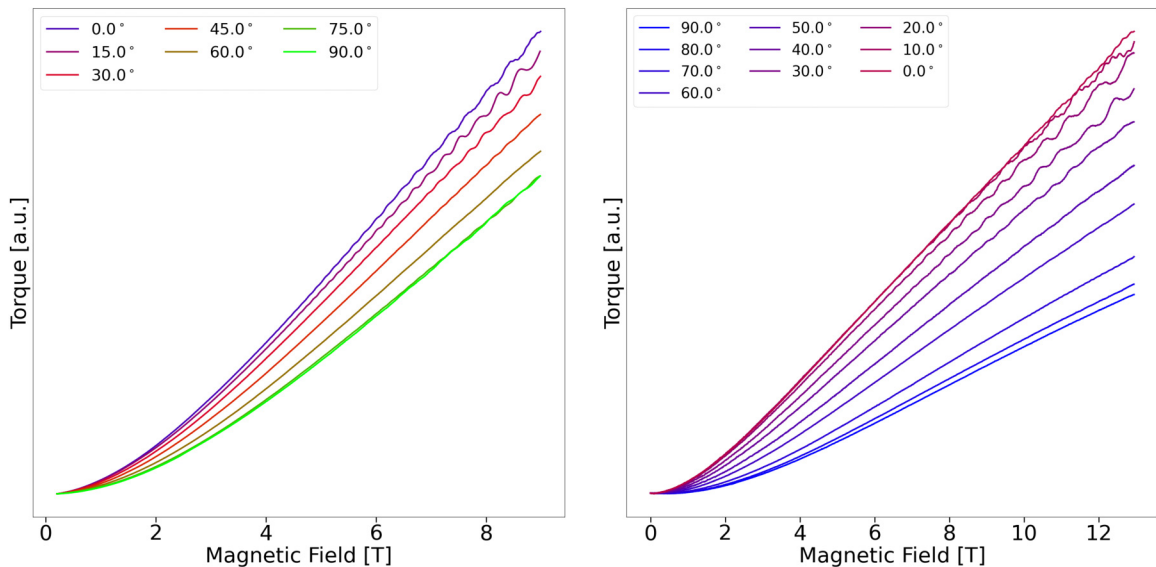


FIG. 11. Magnetic field sweeps of magnetic torque at various angles at 1.8 K for the $\mathbf{B} \parallel a$ - b plane (left) and for the $\mathbf{B} \parallel b$ - c plane (right). The angle 0° corresponds to $\mathbf{B} \parallel b$ in both cases.

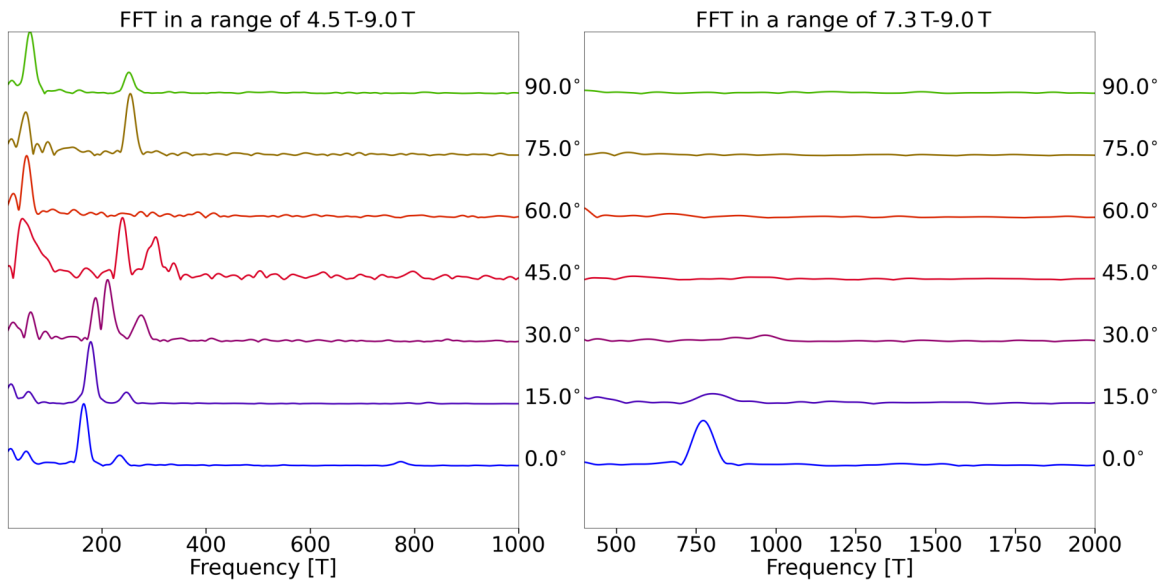


FIG. 12. Fast Fourier transform of the background subtracted magnetic torque data in the $\mathbf{B} \parallel a\text{-}b$ plane at 1.8 K. The angle 0° corresponds to $\mathbf{B} \parallel b$.

APPENDIX E: RAW DATA FOR TRANSPORT AND THERMOPOWER

The residual resistance ratio along the a - and c -axis are shown in Fig. 14, where the anisotropy of this material becomes apparent. We also include thermopower data which was not discussed in the main text.

APPENDIX F: RAW DATA FOR MAGNETORESISTANCE

Magnetoresistance data and respective FFT are shown in Fig. 15. In Fig. 16, the analysis of those quantum oscillations was performed in a similar fashion as with the magnetization data. Dingle temperature, dHvA frequency, effective mass and Berry phase can be extracted from the raw data.

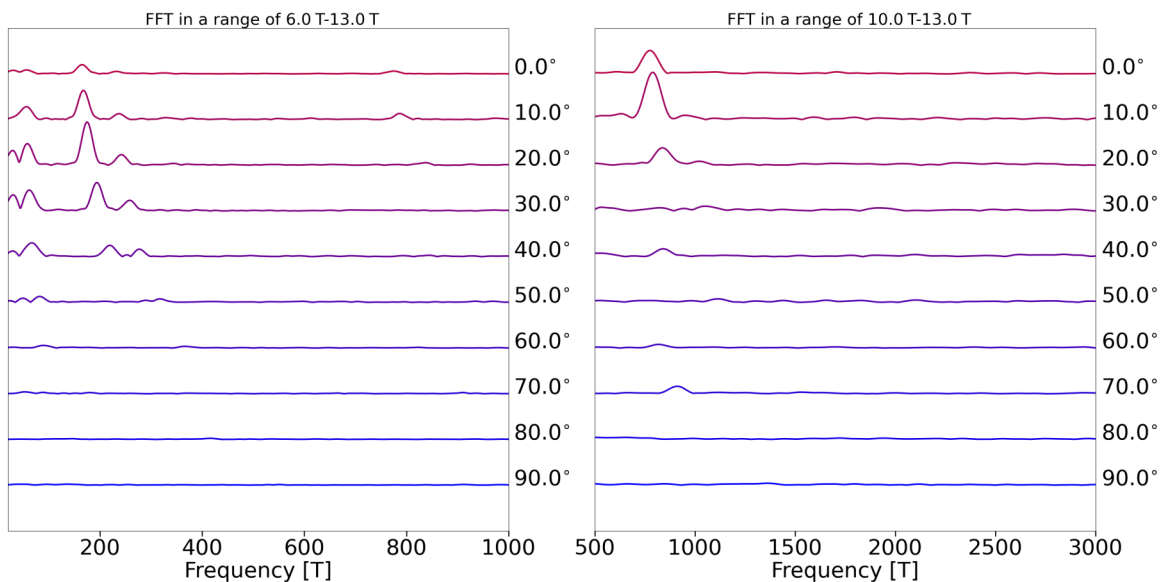


FIG. 13. Fast Fourier transform of the background subtracted magnetic torque data in the $\mathbf{B} \parallel b\text{-}c$ plane at 1.8 K. The angle 0° corresponds to $\mathbf{B} \parallel b$.

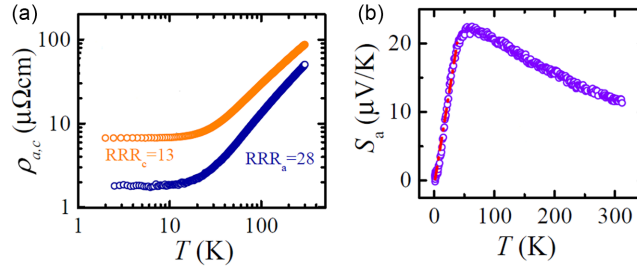


FIG. 14. (a) Temperature dependence of the resistivity with $RRR_a = 28$ and $RRR_c = 13$ in the temperature range from 300 K down to 2 K. (b) Temperature dependence of the Seebeck coefficient along the a axis in the temperature range from 300 K down to 2 K.

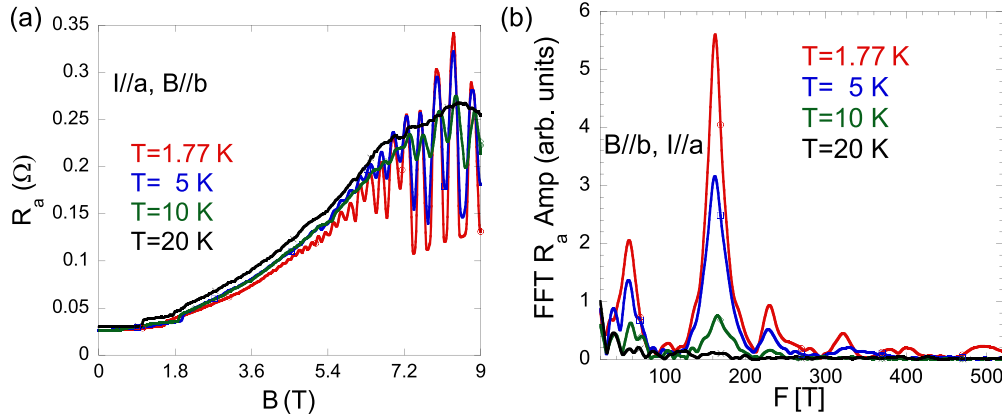


FIG. 15. (a) Magnetic field sweeps of the resistance at various temperatures between 1.77 K and 20 K. (b) Corresponding FFT spectra generated from the raw data between 6 T and 9 T.

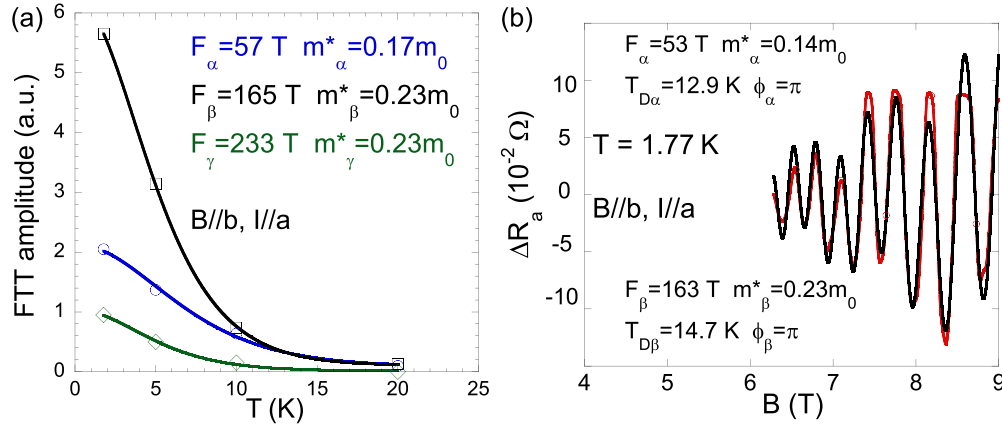


FIG. 16. (a) Fits of the temperature damping factor R_T in the LK formula to the FFT amplitudes. (b) The oscillatory component of the background-subtracted resistance and corresponding fit at $T = 1.77$ K.

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