Magnetization and electrical-transport investigation of the dense Kondo system CeAgSb$_2$

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Of the dense Kondo materials in the class CeTSb$_2$ (where $T$=Au, Ag, Ni, Cu, or Pd), CeAgSb$_2$ is special due to its complex magnetic ground state, which exhibits both ferromagnetic and antiferromagnetic character below an ordering temperature $T_O \sim 9.8$ K. To further elucidate a description of this magnetic ground state, we have carried out a systematic study of single crystalline CeAgSb$_2$ by magnetic, electrical magneto-transport, and Shubnikov-de Haas (SdH) studies. We have constructed the magnetic phase diagram based solely on magnetoresistance data. Here, depending on the orientation of the magnetic field $H$, either ferromagnetic or antiferromagnetic ordering occurs below $T_O$. At zero field the temperature-dependent resistivity below $T_O$ is most consistent with antiferromagnetic order, based on the transport theory which includes magnon scattering. The crystal-field-effect theory applied to the susceptibility data yields splitting energies from the ground state to the first and second excited states of 53 K and 137 K, respectively. Based on different models to determine the Kondo temperature $T_K$, we can obtain both low-temperature and high-temperature estimates for $T_K$ of $\sim 23$ K and $\sim 65$ K, respectively. In the Fermi surface studies, the measurements show very small Fermi surface sections, not predicted by band-structure calculations, and the SdH amplitudes are very sensitive to field direction.

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1. I. INTRODUCTION

Cerium intermetallic compounds exhibit a variety of phenomena such as heavy fermion, superconducting, Kondo insulating, anisotropic transport, and magnetic ordering behavior.1–6 Of current interest in this class of materials are Ce compounds in the tetragonal ZrCuSi$_2$ structure (P4/nmm) including CeCuAs$_2$ and CeTSb$_2$ (where $T$=Au, Ag, Ni, Cu, or Pd). These compounds exhibit competition between the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction and the Kondo effect, which leads to either magnetic or nonmagnetic ground states depending on the strength of the magnetic exchange interaction $J_{\text{ex}}^{\text{ex}}$ between the conduction electrons and localized 4$f$ spins.7 For instance, Sengupta et al.8 found non-Fermi liquidlike behavior at a low temperature in CeCuAs$_2$, where the resistivity shows $T^0.6$ dependence and no long-range magnetic order is observed.8 Besides the RKKY interaction and Kondo effect, the crystalline electric field (CEF) also plays a significant role in determining their magnetic properties. The CEF analysis provides important information about the hybridization effect. In addition, as proposed by Levy and Zhang, the CEF potential depends on the hybridization between the conduction band states and the localized $f$-electron states, which is responsible for the heavy fermion behavior.10

Of particular interest is CeAgSb$_2$, following the report of weak ferromagnetic order in polycrystalline samples by Sologub et al.11 On the basis of magnetization studies, it was shown11 that this compound exhibits a transition below 12 K with a net ferromagnetic moment of 0.15$\mu_B$/Ce at 5 K. The crystal structure of CeAgSb$_2$ consists of Sb- CeSb- Ag- CeSb- Sb layers along [001] with lattice constants $a=4.363$ Å and $c=10.699$ Å, as shown in Fig. 1.3,12 Several different groups have investigated the magnetic properties of CeAgSb$_2$, with conflicting results for the interpretation of the magnetic ground state.6,7,13–16 For instance, Muro et al.13 suggested a ferrimagnetic ground state in polycrystalline samples with a spin-flip field of about 1.3 T. However, this result disagrees with muon spin rotation ($\mu$SR) measurements where spectra in both the ordered state and paramagnetic state indicate a single crystallographic and magnetic muon site.16 Nevertheless, in accordance with $\mu$SR measurements,16 it is very difficult in polycrystalline samples to differentiate between a simple ferromagnetic structure and...
a complex antiferromagnetic structure with a resultant ferromagnetic component. Neutron-power diffraction measurements indicate that the magnetic moment is oriented along the c axis with a Curie temperature of about 9.5 K, but with a smaller saturation moment of $\sim 0.4\mu_B$/Ce. Inelastic neutron scattering$^{17}$ and $\mu$SR experiments$^{16}$ indicate relatively high Kondo temperatures of 60 to 80 K and 60 K, respectively. However, the magnetic entropy reaches$^3$ almost $R \ln 2/(\text{mol Ce})$ at the ordering temperature $T_O$, suggesting that the Kondo temperature is less than $T_O$, based on entropy arguments.$^{19}$ Complex features indicating anisotropy are also evident in electronic transport measurements.

Recent measurements of the de Haas-van Alphen (dHvA) effect$^5$ have been used to study the Fermi surface of this compound. The electronic specific heat coefficient $\gamma$ of single-crystal$^{20}$ CeAgSb$_2$ is 65 mJ K$^{-2}$ mol$^{-1}$ (75 mJ K$^{-2}$ mol$^{-1}$ for polycrystalline samples$^6$) indicative of heavy mass carriers. Effective cyclotron masses from dHvA measurements for fields along the c axis are between 0.85$m_e$ ($m_e$ is free electron mass) and 32$m_e$, for dHvA frequencies between 41 T and 11.2 kT. The band-structure calculations predict that the Fermi surface of CeAgSb$_2$ has a large dHvA frequency of 10.7 kT and several branches with the dHvA frequencies between 4 kT and 9 kT.$^5$ Only one previous Shubnikov-de Haas (SdH) measurement has been reported for magnetic field parallel to the c axis. Here, a single orbit of $\sim 25$ T has been observed at 1.2 kbar in the range 18 T at 2.1 K.$^{21}$

The purpose of the present work is to investigate in more detail some aspects of single-crystal CeAgSb$_2$ samples to clarify the assignment of a magnetic ordering in the ground state and to further explore the behavior of the Fermi surface through the quantum oscillations. In particular, detailed studies of the temperature-dependent magnetoresistance can be described by terms involving scattering due to magnons in addition to simple Fermi liquid behavior ($\rho \sim T^2$). This leads to a description of an anisotropic magnetic ground state. Here, ferromagnetic and antiferromagnetic order depends on magnetic field direction. We find that the magnetization and susceptibility are well described by CEF theory where the energy level parameters are consistent with inelastic-neutron-scattering experiments. In addition, we find, as in a previous report, that one quantum oscillation dominates the SdH spectrum, which is smaller in extremal area than any oscillation seen in the previous dHvA study. Angular-dependent SdH studies further reveal unusual aspects of the Fermi surface of this compound.

II. EXPERIMENTS

Single crystals of CeAgSb$_2$ were made with excess Sb as a flux. The starting materials were placed in an alumina crucible and sealed under vacuum in a quartz ampule, heated to 1150 °C, and then cooled slowly to 670 °C and centrifuged to remove the flux. The dc resistivity data were measured using a conventional four-probe method with current applied in the ab plane. The typical size of a single crystal is 2.5 mm × 1 mm × 0.3 mm.

The magnetization studies were carried out in a superconducting quantum interference device (SQUID) magnetometer over the temperature range 1.8–300 K in the field range 0–5.5 T. Shubnikov-de Haas measurements were performed in both a 33 T resistive magnet in a helium-4 cryostat and separately in a 18 T superconducting magnet with a dilution refrigerator.

III. RESULTS AND ANALYSIS

A. Electrical transport properties

The dc resistivity of a single crystal of CeAgSb$_2$ vs temperature in the range room temperature to $\sim 300$ mK is shown in Fig. 2. At high temperatures the scattering is phonon dominated and the resistivity decreases with decreasing temperature. However, below $\sim 150$ K, the resistivity increases logarithmically as the temperature decreases, which is characteristic of a Kondo lattice system. Below $\sim 15$ K, the resistivity exhibits behavior marked by a drop in resistivity as denoted by $T_{max}$ (see the inset of Fig. 2). In the system, where there is magnetic ordering in the Kondo lattice, the value of $T_{max}$ has to be considered as a function of both Kondo temperature and the mean RKKY interaction strength.$^{22}$ We are able to fit the temperature dependence of the resistivity in the range $\sim 300$ K–$\sim 30$ K, as shown in the inset of Fig. 2, by using

$$\rho(T) = \rho_0^{-C_1 \ln T + C_2 T^2} \int_0^{\Theta_D/T} \frac{\chi}{(e^\chi - 1)(1-e^\chi)} d\chi, \quad (1)$$

where $\rho_0$ is the resistivity due to spin disorder, $C_1$ is the Kondo coefficient, $C_2$ is a temperature-independent constant related to the electron-phonon interaction strength, and $\Theta_D$ is the Debye temperature. The second and third terms of Eq. (1) describe the characteristic single-ion Kondo effect and the electron-phonon scattering, also known as the Bloch-Grüneisen relation,
resistivity due to electrons scattering from an arbitrary type of boson excitation (magnon or phonon) can be written as

$$\rho_B = \frac{m \pi N(0)}{ne^2} \int_0^{2k_F} \frac{k^3}{k_F} \frac{h \omega_k}{4 \pi} \frac{\int d\Omega k |g|^{2} e^{-|g|^2/k_BT}}{4 \sin^2 \frac{2k_BT}{2k_B}}. \tag{2}$$

Here, \(n = k_F^3/3 \pi^2\) is the number density of the charge carriers, \(N(0) = mk_F^2/2\pi^2\hbar^2\) is the density of states per spin at the Fermi level, \(2k_F\) represents the maximum wave-vector transfer, \(g\) is the electron-boson coupling, \(k_B\) is the Boltzmann constant and \(h \omega_k\) is the boson energy for a given wave vector \(k\). We shall apply Eq. (2) to either the ferromagnetic or antiferromagnetic case, as derived in the appendices.

The total resistivity below the transition temperature can be written as

$$\rho_{FM} = BT\Delta \left(1 + \frac{2T}{\Delta}\right) e^{-\Delta/T},$$

or

$$\rho_{AFM} = C \Delta^5 e^{-\Delta/T} \left\{ \frac{1}{5} \left( \frac{T}{\Delta} \right)^5 + \frac{1}{4} \left( \frac{T}{\Delta} \right)^4 + \frac{5}{3} \left( \frac{T}{\Delta} \right)^3 \right\}. \tag{3}$$

In the gapless limit \(\Delta \rightarrow 0\), we obtain \(\rho \sim T^2\) and \(\sim T^3\) from Eq. (3) for the ferromagnetic (FM) case and the antiferromagnetic (AFM) case, respectively, as discussed in Ref. 22. In practice, to apply Eq. (3) to our data, we fit the first two terms of Eq. (3) at a very low temperature (0.7 K to \(\sim 3\) K) to obtain \(\rho_0\) and \(A\), as shown in the inset of Fig. 3. These parameters are then fixed and the parameters in Eq. (3) are obtained by a higher temperature fit up to \(\sim 8\) K for both FM and AFM cases. We find the parameters corresponding to this fit are \(\rho_0 = (0.17 \pm 0.03) \mu\Omega\) cm, \(A = (0.08 \pm 0.01)\) \mu\Omega\) cm K\(^{-2}\); \(B = (3.3 \pm 0.2) \mu\Omega\) cm K\(^{-2}\), \(\Delta = (24.4 \pm 0.5) K\) (FM) and \(C = (1.30 \pm 0.02) \times 10^{-3} \mu\Omega\) cm K\(^{-5}\), \(\Delta = (10.5 \pm 0.5) K\) (AFM). Although small, there is a significant difference between these two fits at lower temperatures and fields. By applying this fitting procedure to the field-dependent resistivity for \(H \perp c\) axis, we

FIG. 3. Temperature dependence of the in-plane dc resistivity of a single crystal of CeAgSb\(_2\) at a low temperature. The solid line indicates \(T^2\) dependence and the dashed and dotted line indicate the full fit to Eq. (3) for FM and AFM, respectively. Inset: low-temperature fit of \(\rho = \rho_0 + aT^2\).

FIG. 4. (a) The in-plane dc resistivity (curves offset for clarity) vs temperature for different fields \((H \perp c\) axis). The dotted and dashed-dotted lines indicate fits to FM and AFM, respectively. (b) The field dependence of AFM gap energy \(\Delta_{AFM}\). The dashed line is a guide to the eye.
are able to see more clearly these differences, as shown in Fig. 4, where in the low field limit, the AFM description gives the best fit. This suggests antiferromagnetic ordering in the basal plane below $T_O$. At higher fields, the spins will align parallel to the external magnetic field, favoring ferromagnetic order. We have determined the effect of the magnetic field on the AFM energy gap $\Delta_{AFM}$, as shown in Fig. 4, and find the magnetic field reduces the gap energy. This is not surprising because in the antiferromagnetic case, the gap will be modified by $\Delta_B=\Delta-\mu_{eff}H_{eff}$, where $\mu_{eff}$ is the effective magnetic moment and $H_{eff}=H-H_M$ which is the sum of the applied magnetic field and molecular field $H_M$ produced by the other moments. In contrast, for $H\parallel c$ axis, both FM and AFM fits work well at low fields, but only the FM fit is adequate at higher fields. Thus, this suggests that the ferromagnetic ordering is along the $c$ axis.

The effect of magnetic field on the ordering temperature $T_O$ is shown, for both magnetic fields applied parallel and perpendicular to the $c$ axis in Fig. 5. We use the minimum of the second derivative of the resistivity with respect to the temperature $[(d^2\rho/dT^2)]=0$ as the criterion for the ordering temperature, which is indicated by an arrow in Fig. 5. We observed that the ordering temperatures have different behavior depending on the direction of the applied magnetic field. For $H \perp c$ axis, $T_O$ decreases as the external field increases, following antiferromagnetic behavior. In contrast, for $H\parallel c$ axis, $T_O$ increases as the external field increases, which is consistent with the ferromagnetic order. From this analysis, we attempt to construct the magnetic phase diagram of this compound, as shown in Fig. 6. This result is similar to that obtained in Ref. 7, which is estimated from the magnetization and the thermal expansion measurements. We will see later that this magnetic phase diagram is consistent with the CEF analysis.

The magnetoresistance (MR) of this compound, defined as $(\rho(H,T)-\rho(0,T))/\rho(0,T)$, for the two different orientations is shown in Fig. 7. The MR changes sign below a characteristic temperature $T_m$ from negative to positive.
FIG. 8. (a) Temperature dependence of the susceptibility of CeAgSb$_2$ both for field applied parallel and perpendicular to the c axis, at $H$=0.1 T. (b) Field dependence of magnetization for two different field directions at $T$=2 K. The dashed lines are guides to the eye. Inset: the magnetization at low field for $H$//c axis.

Here, $T_m$ also decreases or increases depending on the direction of the applied field (see the insets in Fig. 7). The anisotropy of $T_m$ also suggests that the system has different magnetic ordering for the different field directions. In both cases, $T_m$ saturates at a certain field. The behavior of the MR above and below $T_m$ can be explained as follows. Above $T_m$, the negative character of the MR is due to the reduction in electron-spin scattering, since as the magnetic field increases, the effective field suppresses the fluctuations of the localized spins, leading to an increase in the conductivity. Below $T_m$, when the magnetic field increases, the gap energy $\Delta$ decreases and more magnons will be in the excited state, which causes more electron-magnon scattering, increasing the resistance.

B. Magnetic properties

The magnetization measurement of CeAgSb$_2$ exhibits magnetic ordering below $T_g \sim$9.8 K as shown in Fig. 8(a), where we note that below $T_g$ the magnetization is anisotropic with respect to field direction. The temperature dependence of the magnetization under 0.1 T for the field perpendicular to the c axis shows a cusp around $T_g$, which is usually found in an antiferromagnetic transition. We have used the Curie-Weiss law to fit the susceptibility data at high temperature. For $H$//c the effective magnetic moment and Curie temperature are $\mu_{\text{eff}}$=2.51$\mu_B$/Ce and $\Theta_C$=−63.9 K. For $H$//c, $\mu_{\text{eff}}$=2.48$\mu_B$/Ce and $\Theta_C$=5.05 K. Both effective magnetic moments are close to the theoretical value of 2.54$\mu_B$/Ce for Ce$^{3+}$ ($S=\frac{1}{2}$, $L=3$; $J=\frac{3}{2}$). The magnetization isotherm for $H$//c data at $T$=2 K, as shown in Fig. 8(b), increases almost linearly below 3.5 T and then remains nearly constant at high field with a saturated moment $\sim$1.2$\mu_B$/Ce. No hysteresis is found, suggesting this compound is antiferromagnetically ordered for $H$//c. In contrast, for $H$//c, a saturation magnetic moment of $\sim$0.4$\mu_B$/Ce is found at a low field ($\sim$0.04 T). Hysteresis with a remnant magnetic field $\sim$0.01 T is observed, as shown in the inset of Fig. 8(b), indicating ferromagnetic order.

The Kondo temperature for a single-ion and nonmagnetic order can be estimated by using

$$T_K = \frac{(n-1)\pi RW}{6\gamma},$$

where $n=2J+1=2$, $W$ is the Wilson number=1.289, $R$ is the universal gas constant=8.314 J mol$^{-1}$ K$^{-1}$ and $\gamma$ is the Sommerfeld coefficient $\sim$244 mJ mol$^{-1}$ K$^{-2}$. We estimate the Sommerfeld coefficient by using $[C(T)/T]=\gamma+aT^2$, where $C$ is the specific heat, in the temperature range between 20 K and 12 K, which is above the ordering temperature. The Kondo temperature obtained from Eq. (4) is $T_K$=23 K, which is similar to $T_{\text{max}}\sim 15$ K (see Fig. 2). This comes from the doublet ground state in the CEF analysis and the low-temperature estimate for $T_K$.

In contrast to the above approach, if we consider multiplet states ($J=\frac{5}{2}$) from the CEF analysis then we obtain a high-temperature estimate for $T_K$ of $\sim$65 K, which is derived from the inverse susceptibility data (see Fig. 9). This high-temperature $T_K$ is comparable to the inelastic neutron scattering ($T_K$ is between 60 and 80 K) and $\mu_{\text{SR}}$ ($T_K \sim$60 K).

1. Crystalline electric field theory

We next discuss the magnetic properties based on the CEF theory. The total Hamiltonian is given as follows,
ers ion with a doublet ground state. The CEF effect splits the tetragonal symmetry, can be written as a linear field. The CEF Hamiltonian of this system, which has a molecular field contribution is given by

\[ H_{CEF} = g_i \mu_B M_i (H + \lambda_i M_i), \]

where \( g_i \) is the Landé g factor (\( \frac{2}{3} \) for Ce\(^{3+} \)), \( \mu_B \) is the Bohr magneton, \( J_i \) (\( i = x, y, \) and \( z \)) is the component of angular momentum, \( M_i \) is the magnetization, and \( H_{CEF} \) is the CEF Hamiltonian. The second and third terms of the Hamiltonian are the contributions from the Zeeman effect and the molecular field. The CEF Hamiltonian of this system, which has a tetragonal symmetry, can be written as

\[ H_{CEF} = B^0_i O^0_i + B^2_i O^2_i + B^4_i O^4_i, \]

where \( B^i \) and \( O^i \) are the CEF parameters and the Stevens operators, respectively.\(^{29,30} \) The Ce\(^{3+} \)(4f\(^4 \)) ion has an odd number of electrons in the 4f shell and qualifies as a Kramers ion with a doublet ground state.\(^{30} \) The CEF effect splits the 4f level into three doublets with excitation energy \( \Delta_1 \) and \( \Delta_2 \) from the ground state to the first and second excited states, respectively. The temperature dependence of the susceptibility based on CEF model can be expressed as

\[ \chi_{CEF} = N(g_i \mu_B)^2 \left( \frac{1}{Z} \sum_{n \neq n'} | \langle m | J_i | n \rangle |^2 \right) - \frac{1 - e^{-\Delta_{mn} / k_B T}}{\Delta_{mn}} \times e^{-\Delta_{mn} / k_B T} + \frac{1}{k_B T} \sum_{n \neq n'} | \langle n | J_i | n \rangle |^2 \times e^{-E_n / k_B T}. \]

Here, index \( i \) indicates the axis (\( x, y, \) or \( z \) axis), \( N \) is the number of ions, \( E_n \) is the energy at state \( n \), \( Z \) is a partition function, and \( \Delta_{mn} = E_n - E_m \). The total magnetic susceptibility including the molecular field contribution is given by

\[ \chi^{-1} = (\chi_{CEF})^{-1} - \lambda_i. \]

Consistent with previous results.\(^7 \) Also, the excitation energies of ~60 K and ~145 K are consistent with neutron-scattering experiments.\(^18 \) The molecular field parameter \( \lambda \) is proportional to the exchange interaction between nearest neighbors and is negative (positive) for the antiferromagnetic (ferromagnetic) case. In Table I, we find \( \lambda \) is negative for the \( H \perp c \) and positive for \( H \parallel c \), which is consistent with the magnetic phase diagram obtained from resistivity measurement (see Fig. 6).

C. Shubnikov-de Haas oscillations

The Fermi surface of CeAgSb\(_2\), has been systematically studied by Inada \textit{et al.}\(^5 \) by angular dependent dHvA measurements, which involve the determination of the oscillatory magnetization vs inverse field. The large cylindrical corrugated Fermi surfaces with large cyclotron masses (20–30\( m_e \)) were obtained in Ref. 5. Theoretically, the modified 4f-localized electron band calculation was proposed to explain some of the dHvA frequencies observed in the experiment. We have studied the temperature dependence of the SdH in CeAgSb\(_2\) high fields (32 T) to helium temperatures, and in lower fields (18 T) to 80 mK vs magnetic field direction. In the SdH measurement, the oscillatory magnetoresistance, upon which may be imposed a background magnetoresistance, is measured. In a previous study,\(^21 \) the SdH of CeAgSb\(_2\) under pressure (1.2 kbar) for \( H \parallel c \) showed a single SdH frequency of 25 T. As in Ref. 19, we find the predominant frequency to be ~25 T, as shown in Fig. 10(a), and in the high field (above 25 T), we observe another frequency (~300 T) below 2 K. We note the main oscillation frequency is significantly less than the lowest frequency (~40 T) observed previously in the dHvA measurements.\(^5 \) We find that the amplitude of the 25 T oscillation is highly dependent on field orientation, where a tilt of only 7° away from the \( c \) axis causes a significant decrease in amplitude [Fig. 10(b)]. Figure 11 shows the effective cyclotron mass (\( M_c \)) for the 25 T orbit, which is ~3\( m_e \), extracted from the Lifshitz-Kosevich formula,\(^31 \) where we note that the effective mass, unlike the SdH amplitude, is not sensitive to the small change in angle. The cyclotron mass obtained in the SdH measurements is only 0.85\( m_e \) for the 41 T

| TABLE I. CEF parameters, energy level, molecular field parameters \( \lambda \) and corresponding wave functions for CeAgSb\(_2\). |
|---|---|---|---|
| CEF Parameters | \( B^0_i = 6.60 \) K | \( B^2_i = 0.09 \) K | \( B^4_i = 1.14 \) K |
| \( \lambda_{c-axis} = 47.9 \) mol/emu | \( B^0_i | \frac{1}{2} \rangle = 0.919 \) | \( B^2_i | \frac{1}{2} \rangle = 0.394 \) | \( B^4_i | \frac{1}{2} \rangle = 0.192 \) |
| Energy (K) | \( | \frac{1}{2} \rangle \) | \( | \frac{1}{2} \rangle \) | \( | \frac{1}{2} \rangle \) |
| 137 | 0 | 0 | 0 |
| 53 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

\( g_i \) and \( \mu_B \) are the CEF parameters and the Stevens-operators, respectively.\(^{29,30} \) The Ce\(^{3+} \)(4f\(^4 \)) ion has an odd number of electrons in the 4f shell and qualifies as a Kramers ion with a doublet ground state.\(^30 \) The CEF effect splits the 4f level into three doublets with excitation energy \( \Delta_1 \) and \( \Delta_2 \) from the ground state to the first and second excited states, respectively. The temperature dependence of the susceptibility based on CEF model can be expressed as

\[ \chi_{CEF} = (g_i \mu_B)^2 \left( \frac{1}{Z} \sum_{n \neq n'} | \langle m | J_i | n \rangle |^2 \right) - \frac{1 - e^{-\Delta_{mn} / k_B T}}{\Delta_{mn}} \times e^{-\Delta_{mn} / k_B T} + \frac{1}{k_B T} \sum_{n \neq n'} | \langle n | J_i | n \rangle |^2 \times e^{-E_n / k_B T}. \]

Here, index \( i \) indicates the axis (\( x, y, \) or \( z \) axis), \( N \) is the number of ions, \( E_n \) is the energy at state \( n \), \( Z \) is a partition function, and \( \Delta_{mn} = E_n - E_m \). The total magnetic susceptibility including the molecular field contribution is given by

\[ \chi^{-1} = (\chi_{CEF})^{-1} - \lambda_i. \]
around 95°, which is 5° off from the angles. The amplitude of the oscillation has a maximum expression.

The angular dependence of the SdH signal was studied more systematically at low temperature (80 mK) to 18 T, as shown in Fig. 12(a). We observe two different frequencies (~25 T and ~300 T) depending on the angle between the field and the c axis, as shown in Fig. 12(b). In this sample, we did not detect the 300 T frequency. The inset of Fig. 12(b) shows the amplitude of the 25 T oscillation for different angles. The amplitude of the oscillation has a maximum around 95°, which is 5° off from the c axis, and very dramatically decreases away from 95°. The SdH oscillations below 80° or above 115° are very weak, and no SdH oscillations associated with the 25 T frequency are observable outside this range. Both measurements indicate that the SdH amplitudes are very sensitive to magnetic field direction.

The band calculation suggests that the Fermi surface of CeAgSb₂ is similar to those of LaAgSb₂. The dHvA experiments indicate that the best model is one where the band structure is modified by the 4f-localized electron system. This model has been successfully used to explain the topology of Fermi surfaces in Ce compounds with magnetic order, such as CeAl₂ and CeB₆. However, this model cannot describe all the frequencies observed in both SdH and dHvA measurements in CeAgSb₂. Moreover, the decrease in the SdH frequency away from H//c is inconsistent with a simple two-dimensional cylindrical Fermi surface directed along the c axis. Nevertheless, if the main Fermi surface cylinders are corrugated, as the tilt angle increases, the cyclotron mass and frequency will decrease. Furthermore, the amplitude of oscillation might also be strongly affected by changes in the lens orbit topology as the angle moves away from 90°. The main Fermi surface, which has frequency of 11.2 kT, was not observed in this measurement. This might be due to the relatively large effective cyclotron mass or to some other at present unknown fundamental difference between dHvA (a thermodynamic probe) and SdH (a transport probe) measurements in the present case.

**IV. CONCLUSION**

We have performed magnetic and electrical transport measurements on single crystalline CeAgSb₂ to further explore its magnetic ground state. At the zero field, the magnetic transition, based on transport theory which includes magnon scattering, indicates that antiferromagnetic order appears below \( T_0 \sim 9.8 \) K. The MR data, again compared with the magnon model, shows that at the finite field antiferromagnetic order is present for in-plane field, and the ferromagnetic order for the field along the c axis. One type of magnetic ground state that would lend itself to this anisotropy is a canted antiferromagnetic configuration in the basal plane. However, Araki et al. concluded that the magnetic ground state in the polycrystalline CeAgSb₂ from neutron scattering is a simple ferromagnetic order. It would be very useful to test this contradiction by doing a neutron-scattering experiment on a single crystal to determine in detail the spin alignments.

The magnetic \( H-T \) phase diagram we obtain from MR data is consistent with that found in previous magnetization and thermal expansion measurements. A fit of the magnon model to the data yields a field-dependent magnon energy gap, which is found to decrease with the increasing field. Complementary to the field-dependent magnon gap is the observation that the MR changes sign at a temperature \( T_m \) below \( T_0 \). \( T_m \) depends on the magnetic field and its direction, and we present arguments to describe this effect.

Previous estimates of the \( T_K \) have varied widely. From the doublet ground state \( J=\frac{1}{2} \) and multiplet states \( J=\frac{5}{2} \), we obtain both low-temperature and high-temperature estimates for \( T_K \) of \( \sim 23 \) K and \( \sim 65 \) K, respectively. The high-temperature \( T_K \) is similar to those obtained from preliminary
in agreement with a previous preliminary study, a small (25 T) orbit dominates the SdH signal, indicating significant differences between the SdH and previous dHvA results where no frequency below 40 T is observed. Moreover, unlike the dHvA, there seems to be a very strong attenuation of the SdH signal with field direction. Although SdH is sensitive to Stark-interference-type orbits that have no thermodynamic weight, it is not clear why the 25 T is so evident, or if it does indeed arise from lenslike orbits from intersecting Fermi surface sections at the zone boundaries. It is also possible that the magnetic ground state may influence the electronic structure or the carrier mean-free path in some unknown manner. Further high-field SdH and dHvA comparative measurements are planned to explore these questions.

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APPENDIX A: FERROMAGNETIC CASE

In the case of an anisotropic ferromagnetic (FM) material, there is a gap \( \Delta \) in the magnon spectrum, and the energy dispersion relation of the magnon \( \omega_k \) can be expressed by \( \hbar \omega_k = \Delta + C_0 k^2 \), where \( C_0 \) is the spin-wave stiffness. The electron-magnon coupling \( |g_\parallel|^2 \) for ferromagnetic system is independent\(^{35}\) of \( \vec{k} \). In the limit of \( \hbar \omega_k / 2k_BT \gg 1 \), the leading term of electron-magnon resistivity in the anisotropic ferromagnetic material \( \rho^{FM} \) can be written as

\[
\rho^{FM}(T) = BT \Delta \left( 1 + \frac{2T}{\Delta} \right) e^{-\Delta T}, \tag{A1}
\]

where \( B \) is a constant related to the spin disorder.

APPENDIX B: ANTIFERROMAGNETIC CASE

In the case of antiferromagnetic (AFM) system, the electron-magnon coupling \( |g_\parallel|^2 \) and the energy dispersion relation \( \omega_k = \sqrt{\Delta^2 + Dk^2} \). By using the information given above, we obtain

\[
\rho^{AFM}(T) = \frac{C}{T} \int_0^\infty \frac{k^4 \sqrt{\Delta^2 + Dk^2}}{\sinh^2(\sqrt{\Delta^2 + Dk^2}/2T)} dk, \tag{B1}
\]

where \( C \) is a constant. Using the change of variable, \( y = \sqrt{\Delta^2 + Dk^2}/2T \), one can approximate \( \sinh^2 y = e^{2y} \) in the small temperature limit \( T \ll \Delta \), and find

\[
\rho^{AFM}(T) = CT \int_0^\infty y^2(\sqrt{y^2 - y_0^2})^3 e^{-2y} dy, \tag{B2}
\]

where \( y_0 = \Delta / 2T \). This integral can be easily calculated if we use another change of variable \( y = y_0 \cosh(x) \), so that

\[
\rho^{AFM} = CT y_0^5 e^{-2y_0} \int_0^\infty (\cosh^2 x \sinh^3 x \times e^{-2y_0 \cosh x + 2y_0} dx. \tag{B3}
\]

The integrand of Eq. (B3) is asymptotic to zero above a certain \( x \), so that it can be simplified to \( \cosh^2 x \sinh^3 x \), in which the function \( e^{-2y_0 \cosh x + 2y_0} \) acts as a cutoff in the integral. The limit of the integral then is from 0 to \( x_c \), where \( x_c \) is the solution of \( -2y_0 \cosh x_c + 2y_0 = -1 \), and Eq. (B3) becomes

\[
\rho^{AFM} \approx CT y_0^5 e^{-2y_0} \int_0^{x_c} \cosh^2 x \sinh^3 x dx. \tag{B4}
\]

Thus, the leading term of the resistivity in the antiferromagnetic case is given by

\[
\rho^{AFM} \approx C \Delta^5 e^{-2\Delta T} \left\{ \left( \frac{T}{\Delta} \right)^5 + \left( \frac{T}{\Delta} \right)^4 + \left( \frac{T}{\Delta} \right)^3 \right\}. \tag{B5}
\]
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