Field-temperature phase diagram and entropy landscape of CeAuSb2

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We report a field-temperature phase diagram and an entropy map for the heavy-fermion compound CeAuSb2. CeAuSb2 orders antiferromagnetically below $T_N = 6.6$ K and has two metamagnetic transitions, at 2.8 and 5.6 T. The locations of the critical end points of the metamagnetic transitions, which may play a strong role in the putative quantum criticality of CeAuSb2 and related compounds, are identified. The entropy map reveals an apparent entropy balance with Fermi-liquid behavior, implying that above the Néel transition the Ce moments are incorporated into the Fermi liquid. High-field data showing that the magnetic behavior is remarkably anisotropic are also reported.

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I. INTRODUCTION

CeAuSb2 is a heavy-fermion system with the tetragonal $P4/nmm$ structure, moderate electrical anisotropy, and strong magnetic anisotropy [1]. Although it has not been widely studied, it shows strong phenomenological similarities with other cerium-based compounds that have received intense interest. A major theme of study of these systems is to understand and tune the balance between Kondo and Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction: RKKY interaction couples localized spins and favors a magnetically ordered ground state, while strong Kondo interaction quenches local spins and yields a heavy Fermi liquid. Data presented in this paper, and comparison with other compounds, suggest that CeAuSb2 is on the border, with the effects of both Kondo and RKKY interactions apparent in its bulk properties, but neither dominating.

A field-temperature phase diagram, for field along the easy axis (the $c$ axis), of CeAuSb2 is shown in Fig. 1. The indicated phase boundaries are from this work; however, many of its basic features were published in Refs. [2,3]. At zero field, there is a Néel transition at $T_N = 6.6$ K. As the field is increased, there are two first-order metamagnetic transitions, at 2.8 and 5.6 T; at 1.5 K the magnitudes of the metamagnetic jumps are $\approx 0.3 \mu_B$/Ce and 0.5 $\mu_B$/Ce, respectively [2]. The magnetic order terminates at the second metamagnetic transition.

Interestingly, although the magnetism of CeAuSb2 is very different from that of the isostructural compound CeAgSb2, it is similar to that of a range of less obviously related compounds. CeAuSb2 is an antiferromagnetic with easy-axis anisotropy, while CeAgSb2 has a net ferromagnetic moment, and easy-plane anisotropy [4]. In contrast, the compounds CeNiGe3 [3,6], CeRh$_2$Si$_2$ [7,8], and YbNiS$_3$ [9,10], and the CeRu$_2$S$_2$-based compounds (Ce$_{0.8}$La$_{0.2}$)Ru$_2$S$_2$ [11–13], CeRu$_2$(Si$_{0.9}$Ge$_{0.1}$)$_2$ [14,15], and Ce(Ru$_{0.92}$Rh$_{0.08}$)$_2$S$_2$ [16,17] are all easy-axis compounds, like CeAuSb2. All are antiferromagnets. All of them, like CeAuSb2, show two metamagnetic transitions when the field is directed along the easy axis, and with the exception of Ce(Ru$_{0.92}$Rh$_{0.08}$)$_2$Si$_2$ the magnetic order of each terminates at the second metamagnetic transition. $\chi_c/\chi_a$ of CeAuSb2 is 17 just above $T_N$ [1]; of CeRh$_2$S$_2$, 5 just above its Néel temperature [18]; and of CeRu$_2$Si$_2$, 15 at 10 K [19]. CeNiGe3 is an orthorhombic system where the $a$ axis is the easy axis; $\chi_a/\chi_c$ and $\chi_a/\chi_x$ are 11 and 17, respectively, just above its $T_N$ [5].

Therefore, study of CeAuSb2 is likely to have bearing on a range of other compounds. Comparison with the CeRu$_2$S$_2$-based compounds is of particular interest because of the amount known about that system. CeRu$_2$S$_2$ itself has a Kondo temperature $T_K$ of $\sim 24$ K [19], and strong antiferromagnetic fluctuations at low temperature, but no static order [20]; the Kondo effect appears to win out over the RKKY interaction by a small margin. Substitution can alter the balance: partial substitution of La for Ce, e.g., decreases $T_K$ and induces the static antiferromagnetic order mentioned above [13,21,22]. The substitution applies an effective negative pressure: the

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lattice is expanded, and when it is compressed again with (positive) hydrostatic pressure the antiferromagnetism is suppressed [23]. The similarity between the phase diagrams of CeAuSb2 and substituted CeRu2Si2-based compounds suggests that CeAuSb2 acts, broadly, as a negative-pressure version of CeRu2Si2. Usefully, it is a version without intrinsic substitution disorder or, with reference to Ce1−xLa,xRu2Si2, dilution of Ce spins. It may allow RKKY-Kondo crossover to be studied with positive rather than negative pressure.

The main aim of the present work is to refine the phase diagram of CeAuSb2. The metamagnetic transitions are thought to be first order, but clear hysteresis has not been seen and their critical end points have not been precisely located [2]. As elaborated upon in Sec. VI, the end points may prove crucial to possible quantum criticality in CeAuSb2 and related compounds. In addition to locating the critical end points of CeAuSb2, we also report an entropy map across the field-temperature phase diagram, which yields both similarities and notable contrasts with the above compounds.

II. CRYSTAL GROWTH

Single CeAuSb2 crystals were grown by a self-flux method, similar to that described in Refs. [24,25]. High-purity ingots of Ce (99.99%, Ames Laboratory), Au (99.999%, Alfa Aesar), and Sb (99.999%, Alfa Aesar) were placed in an alumina crucible with a Ce: Au:Sb atomic ratio of 1:6:12. The crucible was then sealed in an evacuated quartz ampoule and heated to a 

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III. RESULTS: RESISTIVITY

For measurement of resistivity, samples were cut into narrow bars with a wire saw. The as-grown samples were naturally thin along the c axis, so polishing to reduce thickness was not necessary. The samples were measured with a typical four-terminal method using a lock-in amplifier, with typically a 100-μA excitation current at a frequency on the order of 100 Hz. Contacts to the sample were made with DuPont 6838 silver paste, baked at 180°C for 2.5 h.

We start in Fig. 2 with a comparison of the resistivities ρ(T) of CeAuSb2, CeRu2Si2, and CeNiGe3. The room-temperature values are similar; respective comparison of CeAuSb2 with LaAuSb2 [26] and CeRu2Si2 with LaRu2Si2 [19] show that at room temperature, where defect scattering gives only a small portion of the resistivity, scattering from cerium spins accounts for roughly half the resistivity, and a greater portion as T is reduced. The resistivities also all show two broad shoulders, marked by the arrows in Fig. 2. The higher-temperature shoulders are due to thermal occupation of excited crystal electric field states. The origin of the lower-temperature shoulders may differ from compound to compound; in CeRu2Si2 it is attributed to the Kondo effect [19]. In both CeNiGe3 and CeAuSb2 the shoulder is at a lower temperature than in CeRu2Si2; both these compounds also show Néel order, so the lower-temperature shoulder could be due to onset of short-range magnetic order at T > TN, or the Kondo effect, or a combination.

Low-temperature measurements of the resistivity of CeAuSb2 were done on two samples from the same growth batch, with cross sections ≈ 180 × 130 and ≈ 250 × 150 μm (the shorter dimension along the c axis). They were measured together in an adiabatic demagnetization refrigerator. Figure 3 shows the resistivity against field of one sample at various fixed temperatures. At the lowest temperatures, ρ increases sharply at the first metamagnetic transition (at applied field H1) and decreases sharply at the second (H2). Elevated resistivity
between $H_1$ and $H_2$ is also seen in CeNiGe$_3$ [5], YbNiSi$_3$ [9], and CeRh$_2$Si$_2$ [7].

Data from increasing-field and decreasing-field ramps are shown together in Fig. 4; magnet hysteresis is excluded by measuring the field with a Hall sensor placed near the sample. Hysteresis in the metamagnetic transition fields shows that the transitions are first order. The magnitude of the hysteresis against temperature is shown in Fig. 4(b); it decreases steadily as the temperature is increased (proving that it is not an artifact of instrument hysteresis), disappearing within experimental resolution above ~5 K for the first and above ~3 K for the second transition.

Rounding of the transitions and residual instrument hysteresis make it impossible to pinpoint the temperatures where the hysteresis ends. To locate the end points more precisely, we analyzed the magnitudes of the resistivity jumps, $|\Delta\rho|$, determined by integrating the peaks in the derivative $d\rho/d(\mu_0 H)$ as illustrated in Fig. 5(a). Rounding introduces moderate systematic error, but by following the same procedure at each temperature, random error is minimized. $|\Delta\rho|$ against $T$ is shown in Fig. 5(b); the error bars are the estimated systematic error. Linear fits through the higher-temperature points locate the end points of the first and second transitions at 5.6 and 3.7 K, respectively.

In Fig. 4, hysteresis is apparent not only in the transition fields, but also in the magnitude of the resistivity across the magnetically ordered region: $\rho$ is larger on decreasing- than on increasing-field ramps. Hysteresis between $H_1$ and $H_2$ has been reported before [2,3]; its origin is not resolved, although antiferromagnetic domain walls are a natural possibility. We add two further observations:

1. There is hysteresis below $H_1$, as well as between $H_1$ and $H_2$.
2. The magnitude of the hysteresis decreases approximately linearly as the temperature is increased, disappearing between 4 and 5 K.

**IV. RESULTS: SPECIFIC HEAT CAPACITY**

The specific heat capacity $C$ of a sample roughly 2 mm across and 0.1 mm thick, with mass 4.0 mg, was measured in a Quantum Design Physical Properties Measurement System. The relaxation time method was used: at each point the sample temperature was raised by 2%, then the relaxation time was measured.

$C/T$ against temperature at selected magnetic fields is plotted in Fig. 6. $C/T$ of LaAuSb$_2$, from Ref. [2], is also shown, as an estimate of the nonmagnetic contribution; up to at least ~7 K it is much smaller than $C/T$ of CeAuSb$_2$. The dominant feature in the low-temperature heat capacity of CeAuSb$_2$ is the Néel transition. At low fields, the peak at $T_N$ is relatively narrow. It is broader in the vicinity of the first
critical end point, at 2.6 T and 5.6 K, and becomes very sharp as the field is increased towards the second critical end point, at 5.2 T and 3.7 K. The inset in Fig. 6 shows C/T against field at T = 1.5 K. It is higher between H1 and H2 than on either side. This behavior has also been established for CeNiGe$_3$ [5], Ce(Ru$_{0.02}$Rh$_{0.08}$)$_2$Si$_2$ [17], and (though less pronounced) Ce$_{0.3}$La$_{0.7}$Ru$_2$Si$_2$ [12].

C/T may be integrated from 0 K at each field to yield the entropy, S. To do so, an extrapolation to 0 K is required, although the data extend to low enough temperature that the precise form of the extrapolation is not critical. We take, at each field, a linear extrapolation from the lowest-temperature data point to 79.5 mJ/(mol K$^2$) at 0 K, which is an apparent base value in the data. A map of the resulting entropy, divided by temperature, is shown in Fig. 7. Below the Néel transition, the entropy is generally higher over the field range $H_1 < H < H_2$ than on either side.

At lower fields, S/T and C/T closely match above $T_N$: at $\mu_0 H = 0.4$ T and $T = 7$ K, S/T and C/T are 0.47 and 0.48 J/(mol K$^2$), respectively. In other words, the magnetic order maintains entropy balance with a Fermi-liquid-like, $T$-independent C/T. (Subtracting C/T of LaAuSb$_2$, as an estimate for the phonon contribution, makes little difference: S/T and C/T are respectively revised to 0.45 and 0.41 J/(mol K$^2$).) Entropy balance with a Fermi liquid suggests that the Ce 4$f$ moments are fully incorporated into the Fermi liquid below some temperature that exceeds $T_N$, such that in the absence of magnetic order C/T would be $T$ independent down to 0 K. This behavior is in contrast to CeNiGe$_3$, YbNiSi$_3$, and Ce$_{0.7}$La$_{0.3}$Ru$_2$Si$_2$. Based on analysis of published data [5,9,28], and taking reasonable extrapolations of C/T to 0 K, we find that in these compounds S/T at 7 K (above $T_N$ for each) exceeds C/T by more than a factor of 2. (Specifically, S/T and C/T at 7 K are respectively 0.65 and 0.30 J/(mol K$^2$) for CeNiGe$_3$, $\approx$ 0.63 and 0.27 J/(mol K$^2$) for YbNiSi$_3$, and $\approx$0.58 and 0.21 J/(mol K$^2$) for Ce$_{0.7}$La$_{0.3}$Ru$_2$Si$_2$.) In these compounds the 4$f$ moments appear to give a quasi-independent contribution to S/T that is in addition to a Fermi-liquid contribution: the moments are strongly disordered by $T \sim 7$ K, making a large contribution to the total entropy, but at 7 K the dominant contribution to C/T is from the Fermi liquid.

It is also notable that above $T_N$, C/T of CeAuSb$_2$ drops very quickly to its Fermi-liquid value, whereas C/T of each of CeNiGe$_3$, YbNiSi$_3$, and Ce$_{0.7}$La$_{0.3}$Ru$_2$Si$_2$ has a strong decaying tail that extends at least a few kelvin above $T_N$. Such tails are common in local-moment systems, e.g., in PdCrO$_2$ [29], and arise from gradual onset of short-range magnetic order above $T_N$. They provide further evidence that in these compounds the 4$f$ moments and Fermi liquid are quasi-independent systems, while in CeAuSb$_2$ they are not.

At low fields, the entropy of CeAuSb$_2$ above $T_N$ is a substantial fraction of $R \ln 2$: at 0.4 T and 7 K, $S = 3.3 J/(\text{mol K}) = 0.57 R \ln 2$. The $T > T_N$ entropy is gradually suppressed as the field is increased; indicating that the heavy-fermion state is gradually suppressed through polarization of the Ce moments.

V. RESULTS: HIGH-FIELD MEASUREMENTS

To probe the magnetic anisotropy, resistivity and torque magnetometry measurements up to 35 T were performed at the Laboratoire National des Champs Magnétiques Intenses in Grenoble, France. The samples were mounted on a rotatable platform, to vary the field angle. The transport sample was a bar with cross-sectional area $230 \times 90$ $\mu$m$^2$. The dimensions of the torque magnetometry sample were $\sim 250 \times 250 \times 50$ $\mu$m$^3$. Results are shown in Fig. 8.

Previously published measurements showed that $T_N$ is almost independent of in-plane field up to 18 T [2]. Our measurements show similarly that the metamagnetic transition fields are remarkably unaffected by the presence of a strong
in-plane field. In the figure, $\rho$ is plotted against the $c$-axis field, $H_c = H \cos \theta$, with $\theta$ the angle between $\mathbf{H}$ and the $c$ axis. The form of $\rho(H_c)$ changes little as the in-plane field is increased, even to the point that $\mathbf{H}$ is only a few degrees out of the plane.

The metamagnetic transitions are also apparent in the torque data. Plotted in the bottom panel of Fig. 8 is the torque $N$ divided by the in-plane field $H \sin \theta$: if the field-induced magnetization is pinned to the $c$ axis, and is a function of $H_c$ alone (i.e., independent of the in-plane field), then the graph of $N/H \sin \theta$ against $H_c$ will be independent of field angle. The data show that this is essentially the case for CeAuSb$_2$ up to $\theta \sim 70^\circ$, confirming that the magnetism of CeAuSb$_2$ is strongly easy-axis type. As the field gets very close to the $ab$ plane, the metamagnetic transitions move to lower $H_c$.

VI. PHASE DIAGRAM AND DISCUSSION

Figure 9 shows the field-temperature phase diagram derived from the resistivity and specific heat data presented above. The first-order metamagnetic transition lines, and their critical end points, are indicated. The first metamagnetic line separates regions of magnetic order that may be designated the A and B phases. The line slopes leftward as $T$ is raised, consistent with the observation that the B phase has higher entropy than the A phase. In contrast to a previous report, we do not find evidence for an intermediate phase along either metamagnetic line [3].

The first critical end point, at a temperature of 5.6 K, appears to lie $\approx 0.4$ K below $T_N$ at that field, although the present data do not allow this to be concluded with high certainty. It would be useful to investigate the metamagnetism further, for example through ac susceptibility measurements [30]. If the end point is indeed below $T_N$, it would be interesting to determine whether the boundary between the A and B phases continues to $T_N$ as a crossover or a second-order transition; the former implies adiabatic continuity between the two phases, and the latter an additional symmetry breaking.

Quantum criticality is a major theme in the study of heavy-fermion systems, and in studies of criticality the location of critical end points is vital knowledge. For example, many key properties of CeRu$_2$Si$_2$ are explainable by a missed quantum critical end point at $\mu_0 H \approx 7.6$ T [31]. At the field-driven antiferromagnetic quantum critical point of YbRh$_2$Si$_2$, it has been proposed that it is in fact close proximity of a metamagnetic critical end point and an antiferromagnetic quantum critical point (QCP), rather than the antiferromagnetic QCP alone, that drives the observed divergences in the Sommerfeld coefficient and magnetic susceptibility [32–34]. The superconductivity of URhGe [35] and the anomalous phase in Sr$_3$Ru$_2$O$_7$ [30] both form around low-temperature metamagnetic critical end points.

In CeAuSb$_2$, the second critical end point is at a temperature of 3.7 K. This is more than half the maximum $T_N$, so quantum critical scaling to $T \sim 0$ K is not expected. However, it would be a very compelling experiment to track the end points with pressure, and to attempt to drive them to 0 K. (This may also be achievable with very high in-plane field: the data in Fig. 8 show some reduction of the $c$-axis transition fields with 30-T-scale in-plane fields.) The antiferromagnetic order of both CeRh$_2$Si$_2$ and CeNiGe$_3$ can be suppressed with pressure, with superconductivity appearing in a window of pressure around the antiferromagnetic QCP [36,37]. It would be interesting to determine whether metamagnetic quantum criticality is also involved in this superconductivity. Regarding CeAuSb$_2$, a published pressure study at $H = 0$ showed that pressure initially increases the temperature of the first resistivity shoulder and decreases $T_N$ [26].

As described above, entropy balance with a Fermi liquid suggests that Kondo coupling is important in CeAuSb$_2$, incorporating the 4$f$ moments into the Fermi liquid by some temperature that exceeds $T_N$; strong Kondo coupling probably...
sets in at the temperature of the first resistivity shoulder, at \( \sim 12 \) K. Phenomenologically, CeAuSb\(_2\) therefore appears to be intermediate to CeRu\(_2\)Si\(_2\), where Kondo coupling is strong enough that static magnetic order never emerges, and, e.g., CeNiGe\(_3\) and Ce\(_{0.7}\)La\(_{0.3}\)Ru\(_2\)Si\(_2\), where the moments and conduction electrons appear to be quasicoupled at all temperatures.

We also note a strong similarity between the phenomenology of CeAuSb\(_2\) and Sr\(_3\)Ru\(_2\)O\(_7\), which was in fact the original motivation for this study of CeAuSb\(_2\): both show strongly enhanced resistivity over a finite window of field (in the case of Sr\(_3\)Ru\(_2\)O\(_7\), between \( \approx 7.9 \) and 8.1 T), bounded by first-order metamagnetic transitions, and over which the entropy is also higher \([30,38]\). Sr\(_3\)Ru\(_2\)O\(_7\) is very clearly an itinerant system, while in CeAuSb\(_2\) the moments probably have strong local character below \( T_N \). The similar behavior in spite of this major qualitative difference suggests a deep link between the two systems.

VII. CONCLUSION

In conclusion, we have produced a refined field-temperature phase diagram of CeAuSb\(_2\), and an entropy map spanning the region of magnetic order. We have also highlighted similarities between CeAuSb\(_2\) and other compounds. The observed metamagnetic transitions were sufficiently sharp to resolve clear hysteresis and to locate their critical end points, showing that CeAuSb\(_2\) can now be grown with sufficiently low disorder to make it a useful reference material and target for further study.

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The raw data for the figures in this article can be found in Ref. [39].

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