Nematic State in CeAuSb₂

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At ambient pressure and zero field, tetragonal CeAuSb₂ hosts stripe antiferromagnetic order at $T_N = 6.3$ K. Here, we first show via bulk thermodynamic probes and x-ray diffraction measurements that this magnetic order is connected with a structural phase transition to a superstructure that likely breaks $C_4$ symmetry, thus signaling nematic order. The temperature-field-pressure phase diagram of CeAuSb₂ subsequently reveals the emergence of additional ordered states under applied pressure at a multicritical point. Our phenomenological model supports the presence of a vestigial nematic phase in CeAuSb₂ akin to iron-based high-temperature superconductors; however, superconductivity, if present, remains to be discovered.

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I. INTRODUCTION

Heavy-fermion systems, which consist of a lattice of f electrons that hybridize with the conduction electron sea, host prototypical examples of strongly correlated electronic states [1–4]. In particular, tetragonal Ce-based compounds often reveal novel quantum states of matter in the vicinity of a quantum critical point (QCP) at which a magnetic transition is suppressed to zero temperature by nonthermal parameters, e.g., pressure, magnetic field, or chemical doping [5,6]. Non-Fermi liquid (NFL) behavior, complex magnetic order, charge order, and unconventional superconductivity (SC) are examples of these states, which have also been observed in copper-oxide and iron pnictide high-$T_c$ superconductors, although often accompanied by electronic nematicity—an electronic state that breaks the rotational symmetry of the underlying lattice but not its translational symmetry [7–9]. The origin of the nematic state, as well as its role on the superconducting state, remains controversial [10]. More recently, evidence for nematicity at high magnetic fields has been found in the heavy-fermion CeRhIn₅ [11], indicating that superconductivity and nematicity may also be intertwined in this class of strongly correlated materials [12]. Recent magnetostriction and nuclear magnetic resonance experiments point to the importance of crystalline electric field (CEF) effects in the putative nematic state of CeRhIn₅ [13,14].

CeT'Sb₂ ($T =$ transition metal) is also a dense Kondo lattice system with pronounced CEF effects [15,16]. The magnetic and CEF ground states of CeT'Sb₂ depend on the transition metal $T$ [16,17], and CeAuSb₂ orders antiferromagnetically below $T_N = 5–6.8$ K depending on the occupancy of the Au site [18–20]. Previous x-ray and neutron diffraction measurements showed that CeAuSb₂ crystallizes in a tetragonal crystal structure ($P4/nmm$) [21,22]. Pressurizing CeAuSb₂ does not suppress $T_N$ to zero temperature but rather induces new phases hindering the appearance of a QCP or SC [20]. The nature of the pressure-induced phases in CeAuSb₂ remains an open question but possibly stems from competing magnetic interactions known to exist in this series of compounds [23,24]. In view of field-dependent properties of CeAuSb₂ at atmospheric pressure [19], application of magnetic fields could shed light on the evolution of the magnetic interactions in CeAuSb₂ under pressure. Unlike pressure, however, magnetic fields are symmetry breaking and tend to localize 4f electrons. In CeAuSb₂, $T_N$ is gradually
suppressed by magnetic fields applied along the \( c \) axis, and two metamagnetic (MM) transitions are observed at \( H_{c1} \sim 2.8 \) T and \( H_{c2} \sim 5.6 \) T at low temperatures \[18\]. The \( H-T \) phase diagram constructed by magnetoresistance measurements reveals that both MM transitions are first order at low temperature \[19\]. In addition, \( H_{c2} \) has a tricritical point at 3.7 K, which may be suppressed under applied pressure \[19\]. A recent neutron diffraction study revealed that at \( H_{c1} \) the magnetic structure changes from a single-\( q \) striped phase with wave vector \( \mathbf{Q}_1 = (\eta, \eta, 1/2) \) \([\eta = 0.136(2)]\) to a multi-\( q \) (woven or checkered) phase with \( \mathbf{Q}_1 = (\eta, \eta, 1/2) \) and \( \mathbf{Q}_2 = (\eta, -\eta, 1/2) \) \[22\]. This ground-state competition again stems from competing magnetic interactions and resembles the single-\( q \) to double-\( q \) magnetic transition observed in pnictides \[25\]. Furthermore, striped phases appear to be ubiquitous in strongly correlated systems including manganites, cuprates, nickelates, and cobaltites \[26-29\].

Remarkably, both striped and woven magnetic phases in CeAuSb$_2$ have twofold rotational symmetry in the \( ab \) plane even though the underlying lattice has fourfold rotational symmetry at high temperatures. As a result, one expects that the lattice will also break tetragonal \( C_4 \) symmetry in the presence of magnetoelastic coupling. In fact, in-plane uniaxial pressure experiments show that the magnetic transitions of CeAuSb$_2$ are sensitive to strain \[30,31\]. The situation thus seems analogous to iron-based high-\( T_c \) superconductors such as NaFeAs ("1111") and LaFeAsO ("1111"), which share the same \( P4/nmm \) space group as CeAuSb$_2$ \[32,33\]. There, the stripe magnetic order is generally preceded by a nematic phase with broken \( C_4 \) symmetry of the underlying lattice, in agreement with general theoretical expectations \[34-37\].

Here, we investigate whether such a nematic state exists in heavy-fermion CeAuSb$_2$. Bulk thermodynamic probes show the presence of two transitions at about 6.5 K and 6.3 K in CeAuSb$_2$, at ambient pressure. X-ray diffraction measurements reveal that the development of zero-field striped magnetic order is connected to a structural transition. Our phenomenological model proposes that this structural transition must be a nematic transition at \( T_{\text{nem}} \geq T_N \). Our results support the scenario in which CeAuSb$_2$ hosts a nematic phase that is not intertwined with superconductivity.

**II. METHODS**

Single crystals of CeAuSb$_2$ were synthesized by a self-flux method described in Ref. \[19\]. The highest \( T_N \) of 6.8 K is achieved in the electrical resistivity when the crystals are close to being stoichiometric, i.e., an average site occupancy of 100\% of Au and residual resistivity ratio (RRR) of about 20. Samples with Au deficiency tend to have lower \( T_N \) \[18,38\]. Single crystals were pressurized to 2.66 GPa using a hybrid Be-Cu/ NiCrAl clamp-type pressure cell. Daphne oil 7373 was used as a pressure-transmitting medium, and lead was used as a manometer \[39\]. The in-plane electrical resistivity of CeAuSb$_2$ was measured using a conventional four-probe technique with an LR700 Resistance Bridge in \( ^3 \)He and \( ^4 \)He cryostats from 300 K to 0.3 K. Magnetization measurements were performed using a commercial superconducting quantum interference device (SQUID), and the specific heat was measured using a commercial small-mass calorimeter that employs a quasi-adiabatic thermal relaxation technique. Thermal expansion along the \( c \) axis was measured at atmospheric pressure using a capacitance cell dilatometer with a resolution in \( \Delta L/L \) of \( 10^{-8} \). X-ray powder diffraction (XPD) measurements were performed at the x-ray diffraction and spectroscopy (XDS) beamline of the Brazilian Synchrotron Light Laboratory in Campinas, which uses a 4-T superconducting multipolar wiggler source \[40\]. The XPD patterns were collected at 20 keV in a transmission geometry using an area detector (MAR345). The sample was mounted at the cold finger of an open-cycle He cryostat (base temperature 2.3 K).

**III. RESULTS**

Specific heat, magnetic susceptibility, and thermal expansion measurements in CeAuSb$_2$ reveal two closely lying transitions. As shown in Fig. 1(a), and highlighted in the inset of Fig. 1(b), two peaks occur in the specific heat at \( T_{\text{nem}} = 6.48 \) K and \( T_N = 6.33 \) K, indicated by arrows. Figure 1(c) shows the temperature dependence of the magnetic susceptibility for \( H_\|\|[001] \), and the presence of two distinct phase transitions is evident in the derivative \( d\chi/dT \) at \( T_{\text{nem}} = 6.53 \) K and \( T_N = 6.33 \) K shown in the inset. We note that the signatures of the two phase transitions in CeAuSb$_2$ in both specific heat and \( d\chi/dT \) are similar to those found in BaFe$_2$As$_2$ due to the nematic and magnetic transitions \[41,42\]. Figure 1(d) shows the temperature dependence of the \( c \)-axis length change, \( \Delta L_c/L_c \), with an anomaly in the vicinity of 6.5 K. This anomaly is not typical of purely magnetic phase transitions \[43,44\], and the linear thermal-expansion coefficient, \( \alpha_c = (1/L_c)(dL_c/dT) \), further reveals a negative peak at \( T_{\text{nem}} = 6.55 \) K as well as a positive peak at \( T_N = 6.33 \) K, respectively [see inset of Fig. 1(d)]. Here, \( T_{\text{nem}} \) and \( T_N \) decrease together when fields are applied along the \( c \) axis, suggesting a strong coupling of the order parameters associated with these transitions. As shown below, \( T_{\text{nem}} \) is associated with a structural transition that likely breaks \( C_4 \) symmetry and \( T_N \) with a magnetic transition to the single-\( q \) stripe phase.

X-ray powder diffraction patterns of CeAuSb$_2$ measured at \( T = 7 \) K and \( T = 3 \) K are shown in Fig. 2. Rietveld refinement of the 7-K data in the published structure \[46\] provides a satisfactory fit in the \( P4/nmm \) cell with lattice parameters \( a = 4.3954(2) \) \( \AA \) and \( c = 10.318(1) \) \( \AA \). As indicated by the black difference line \([I(3K) - I(7K)]\) in Fig. 2, the intensities of most Bragg peaks change
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FIG. 1. (a) Specific heat divided by temperature of CeAuSb₂ at ambient pressure. The inset is a magnified view near the peak position. Arrows indicate the transition temperatures $T_{\text{nem}}$ and $T_N$. (b) Calculated $C/T$ versus reduced temperature for fixed anisotropy $\zeta$ and various inverse nematic coupling strength $\tilde{\alpha}$. The inset gives the derivative of $C/T$ on the experimental data (purple) and of the calculations with $\tilde{\alpha} = 2.7$ (green). The theoretical curve was shifted and averaged over disorder for better comparison with the experimental data; details are given in the Supplemental Material [45]. (c) Temperature-dependent magnetic susceptibility in an applied field of 1 kOe along the $c$ axis. ZFC (zero-field cooled; open circles) and FC (field-cooled; solid circles) curves show two transitions without hysteresis. The inset plots the derivative $d\chi/dT$. (d) Temperature dependence of the thermal expansion $\Delta L/L$ of CeAuSb₂ along [001] at zero field, 1 T, and 2 T applied along the $c$ axis. The inset gives the thermal expansion coefficient.

phase transition can happen in two stages [37]: At $T_{\text{nem}}$, tetragonal symmetry is broken, whereas at $T_N$, both time-reversal and translational symmetries are broken. While it is challenging to develop a microscopic model for CeAuSb₂ that can account for the magnetic and nematic phase transitions in this compound, the thermodynamic properties such as specific heat can be obtained from an appropriate phenomenological model. We consider such a model by using a uniform stripe magnetic order with a two-component order parameter $\mathbf{m} = (\mathbf{m}_1, \mathbf{m}_2)$, with ordering wave vectors $\mathbf{Q}_1 = (\eta, \eta, 1/2)$ and $\mathbf{Q}_2 = (\eta, -\eta, 1/2)$ for $\mathbf{m}_1$ and $\mathbf{m}_2$, respectively. Note that these two ordering vectors are not equivalent in the $P4/nmm$ group, but they are related by a 90° rotation. Up to quartic terms, the Ginzburg-Landau free energy compatible with the symmetries present in CeAuSb₂ is given by

$$F \equiv \frac{1}{2} r_0 (\mathbf{m}_1^2 + \mathbf{m}_2^2) + \frac{\mu}{4} (\mathbf{m}_1 + \mathbf{m}_2)^2 - \frac{\theta}{4} (\mathbf{m}_1^2 - \mathbf{m}_2^2)^2,$$

where $r_0 \propto T - T_N^0$, $u > 0$. This result is identical to the free energy employed to understand the nematic phase of the pnictides [36]. Here, for simplicity, we consider both $\mathbf{m}_1$ and $\mathbf{m}_2$ to be real and that contributions from higher harmonics are neglected. Within a mean-field approximation, at $T < T_N^0$, the free energy is minimized for $0 < q < u$ by developing a stripe magnetic order, with either $\langle \mathbf{m}_1 \rangle$ or $\langle \mathbf{m}_2 \rangle$ becoming nonzero. Such a magnetic order also breaks $C_4$ symmetry down to $C_2$. Therefore, $T_N^0$ marks a simultaneous second-order nematic and magnetic phase transition.

So far, this analysis has neglected the gradient terms in Eq. (1), which describe contributions of magnetic fluctuations to the free energy. Going beyond mean-field analysis and including the effects of magnetic fluctuations, this model generally predicts a nematic transition at $T_{\text{nem}} \geq T_N$, where $T_N$ is the renormalized magnetic transition temperature to the stripe phase [36]. Such a paramagnetic-nematic state is characterized by anisotropic magnetic fluctuations, $\langle \mathbf{m}_1^2 - \mathbf{m}_2^2 \rangle \neq 0$, which spontaneously break the $C_4$ symmetry of the system even though $\langle \mathbf{m}_1 \rangle = \langle \mathbf{m}_2 \rangle = 0$. The fate of the coupled magnetic-nematic transitions depends on the parameters of the phenomenological model, which in our case are the degree of anisotropy of the magnetic fluctuations and the nematic coupling strength. The former is given by the ratio $\zeta \equiv J_z/J$ between the out-of-plane and in-plane effective exchange interactions, whereas the latter is given by the ratio $\tilde{\alpha} \equiv u/g$ of the coefficients of Eq. (1). As shown previously in Ref. [36], for a fixed $\zeta$, large $\tilde{\alpha}$ gives two second-order transitions at $T_{\text{nem}} > T_N$, whereas small $\tilde{\alpha}$ gives a simultaneous first-order transition. In the intermediate $\tilde{\alpha}$ range, two transitions remain, but one of them becomes first order [36] (see Supplemental Material [45] for details). We computed the entropy and heat capacity for a fixed $\zeta$ and decreasing $\tilde{\alpha}$
Our model predicts that below, the magnetic phase transitions become first order and simultaneous at \( T_{N,\text{nem}} \). The difference pattern (black line) emphasizes significant intensity gains, or losses, at most Bragg positions. Green markers and labels indicate the indexation of these peaks in the high-temperature \( P4/nmm \) structure. A lattice distortion is not resolved. Below the structural transition, four additional Bragg peaks are observed (see insets), which are not indexed by the parent phase. As shown in Fig. 3(b), a single peak marked by orange arrows occurs in \( d_T/N/\text{nem} \) at low pressures, and the sum of the calculated \( \Delta C/T \) has a minimum at \( T_{\text{nem}} \) and suggests that CeAuSb\(_2\) at ambient conditions is close to \( \alpha = 2.7 \). Our model predicts that below \( \alpha \), both nematic and magnetic phase transitions become first order and simultaneous at \( T_{\text{nem}} = T_N \). Without a full microscopic theory, it is difficult to determine how the Ginzburg-Landau coefficients depend on the experimentally relevant parameters such as pressure and magnetic field. However, as we show below, our experimental data under applied pressure suggest that hydrostatic pressure might reduce \( \alpha \), thus making the transition first order and simultaneous.

Now, we turn our attention to the field and pressure dependence of the coupled transitions in CeAuSb\(_2\). Figure 3(a) shows the temperature dependence of the in-plane resistivity \( \rho_{ab} \) of CeAuSb\(_2\) under various pressures up to 2.66 GPa. At ambient pressure, a sharp drop in \( \rho_{ab} \) occurs at about 6.8 K. As shown in Fig. 3(b), at low pressure, a single peak marked by orange arrows occurs in \( d_T/dT \). Within the resolution of these data (\( \Delta T \sim 0.08 \) K), this single peak likely encloses both \( T_N \) and \( T_{\text{nem}} \) found in \( C/T, d\chi/dT, \) and \( \Delta C/L \) (\( \Delta T \sim 0.01, 0.02, \) and 0.005 K, respectively). With increasing pressure, \( T_N + T_{\text{nem}} \) is suppressed to 5 K at 2.24 GPa. Above 2.24 GPa, however, the single peak splits into two peaks in \( d_T/dT \), which are indicated by black and red arrows, respectively. Note that \( T_{N2} \) marks a shoulderlike broad peak that increases with increasing pressure and \( T_{\text{nem}} = T_N \) marks a sharp symmetric peak that decreases up to 2.52 GPa but increases above 2.52 GPa. We discuss the origin of these transitions below. Above 2.16 GPa, the results from increasing- and decreasing-temperature ramps are shown together in Fig. 3(b), which are indicated by solid and open symbols, respectively. Interestingly, a hysteresis appears at \( T_{\text{nem}} = T_N \) in \( d_T/dT \), pointing to a first-order phase transition. Hysteresis is not typical of a naked antiferromagnetic (AFM) transition but rather suggests the development of a multicomponent state. At \( T_{N2} \) and \( T_N + T_{\text{nem}} \), however, hysteresis is not observed in the resistivity. To shed light on the temperature-pressure phase diagram shown in Fig. 3(c), we turn to the pressure dependence of the initially coupled transitions estimated via the Ehrenfest relation

\[
\frac{dT_{N/\text{nem}}}{dP} = \frac{V_m \Delta \beta}{\Delta C/T},
\]

where \( V_m \) is the molar volume, and \( \Delta \beta \) and \( \Delta C/T \) are changes of the volume thermal expansion coefficient and the specific heat divided by temperature at the transition. By using the experimental values of \( \beta \) and \( C/T \) at ambient pressure, we obtain \( dT_{N}/dP = 0.37 \) K/GPa and \( dT_{\text{nem}}/dP = -0.77 \) K/GPa (see Fig. S3 [45]); i.e., \( T_{\text{nem}} \) would be suppressed with pressure, whereas \( T_N \) would be enhanced with pressure. These transitions, however, are coupled at low pressures, and the sum of the calculated \( dT/dP \) values (–0.4 K/GPa) is in good agreement with the experimental pressure dependence of the coupled transition, \( d(T_N + T_{\text{nem}})/dP \approx -0.45 \) K/GPa. Similarly, the volume thermal-expansion coefficient of pnictides such as LaFeAsO and BaFe\(_2\)As\(_2\) shows two peaks with opposite signs caused by the nematic and magnetic transitions, which would naively suggest that the pressure dependence
of the two transitions would be opposite [47,48]. These two transitions, however, also decrease together with pressure due to their coupling [49,50]. In our results, the fact that \( T_{N2} \) increases with pressure above the critical pressure suggests that it is associated with a different ordered state not coupled to a tetragonal-symmetry breaking, whose origin will be discussed below.

The temperature-pressure false-color map of the local exponent \( n \) of the temperature dependence of \( \rho_{ab} \) is shown in Fig. 3(c), where \( n = \partial \ln \rho_{ab} / \partial \ln T \) and \( \Delta \rho = \rho_{ab} - \rho_0 = A T^n \). The contour map in Fig. 3(c) provides a proxy for the magnetic scattering in different regions of the phase diagram. Above \( P_c \), the green region \((n \approx 2)\) below \( T_{nem} = T_N \) displays the same behavior as the zero-pressure phase, indicating that the magnetic phase is striped AFM, whereas below \( T_{N2} \) the light-blue region indicates a distinct behavior \((n \approx 1.2)\). In Fig. 5, we show that the power-law behavior in the light-blue region at high pressure is similar to the behavior of the multi-\( q \) AFM phase at ambient pressure and high fields. Therefore, our results suggest that at \( P_c \), the coupled transition at \( T_N + T_{nem} \) becomes (1) a second-order AFM transition to the multi-\( q \) phase at \( T_{N2} \) and (2) a simultaneous first-order structural and magnetic phase transition to the stripe phase at \( T_{nem} = T_N \) due to a finite magnetoelastic coupling. This case suggests the existence of a multicritical point at \( P_c \) indicated by a yellow circle in Fig. 3(c) at which four phases meet: a disordered phase PM, a paramagnetic-nematic phase PMnem, an antiferromagnetically ordered stripe-nematic phase AFM(S)nem, and an antiferromagnetically ordered multi-\( q \) phase AFM(M).

Evidence for a hysteretic first-order transition is further confirmed in Fig. 4(a), which shows the field dependence of the in-plane resistivity under various pressures, for increasing- and decreasing-field ramps applied along the \( c \) axis. At 0.3 K, the first MM transition field \( H_{c1} \) and the second MM transition field \( H_{c2} \) do not change with increasing pressure as shown in Fig. 4(a). At low pressure, the magnetoresistance between \( H_{c1} \) and \( H_{c2} \) monotonically increases with increasing field, in agreement with Ref. [19]. Above 2.16 GPa, however, a hysteretic steplike anomaly at \( H^* \) is observed between \( H_{c1} \) and \( H_{c2} \). Note that \( H^* \) decreases with increasing pressure and temperature (see Fig. S4 [45]). Figures 4(b) and 4(c) show the temperature dependence of \( \rho_{ab} \) and \( \partial \rho / \partial T \) at representative pressures for CeAuSb2 in an applied magnetic field. At 1.85 GPa, the coupled transition at \( T_N + T_{nem} \) turns into two transitions at \( T^* \) and \( T_{N2} \) above \( H_{c1} \). The new field-induced phase transition at \( T^* (H > H_{c1}) \) matches the transition at \( H^* \) (see Fig. S7 [45]).

Figure 5 displays the temperature-magnetic-field false-color map of the local exponent \( n \) of \( \rho_{ab} \) for representative pressures, where \( n = \partial \ln \rho_{ab} / \partial \ln T \) and \( \Delta \rho = \rho_{ab} - \rho_0 = A T^n \). The contour maps show the presence of two distinct regions in the AFM phase diagrams. The single-\( q \) region (S) displays a local exponent \( n \approx 2 \), whereas the multi-\( q \)
region (M) reveals \( n \approx 1 \) at ambient pressure. The similar color map for the exponent \( n \) in Ref. [18] does not display the difference of magnetic scattering between distinct magnetic phases because the color scale of that map is not segmented enough to show the difference of \( n \) between 1 and 2. At 2.52 GPa, the contour map indicates that the pressure-induced new phase in zero field below \( T_{N2} \) is related to the field-driven multi-\( q \) phase at ambient pressure. In order to understand the origin of \( T^* \) and the other phases denoted by (\( M' \), \( M^\prime \), and \( M^* \)) under pressure, the underlying magnetic structures will have to be determined by neutron or nuclear magnetic resonance measurements under applied pressure and field. Interestingly, experiments on CeAuSb\(_2\) under uniaxial strain along the [100] direction also suggest additional magnetic phases [30,31]. In particular, the \( H - T \) phase diagram under applied compression along the [100] direction resembles our phase diagram in Fig. 5(d), but it is not precisely the same [31]. Different effects caused by uniaxial and hydrostatic applied pressure have also been observed in the Fe-based superconductors [51]. Finally, we note that the tricritical point of \( H_{c2} \) indicated by yellow circles in Fig. 5 is not suppressed to zero temperature with pressure (see Ref. [45]).

### IV. DISCUSSION

Striped magnetic phases are ubiquitous in strongly correlated materials [26,29,52,53], and unconventional superconductivity is arguably intertwined with spin and charge stripe correlations in the copper oxides and iron-based materials [27]. However, superconductivity is absent in, e.g., nickel oxides, which also host a stripe pattern within the NiO\(_2\) planes analogous to the CuO\(_2\) planes in copper oxides [28]. Here, we show that the \( f \)-electron system CeAuSb\(_2\) also supports a nematic state in the absence of superconductivity. In CeAuSb\(_2\), the signatures of two phase transitions in various thermodynamic measurements are very similar to signatures for nematic and magnetic transitions in the Fe-based superconductors. Despite the opposite sign of the calculated \( dT/dP \) for the different transitions, the coupled transitions decrease together with pressure initially, as in the iron-pnictide compounds. Unlike the Fe-based materials, however, in CeAuSb\(_2\), an additional transition appears at \( P_c \). Above \( P_c \), this new transition temperature increases with increasing pressure, in contrast to the lower-temperature transition.
The key difference between CeAuSb$_2$ and the Fe-based materials is the absence of superconductivity under pressure. Though nematicity may boost Cooper pairing in the iron-based superconductors, nematic fluctuations may be weak in CeAuSb$_2$ due to the first-order nature of the nematic transition and the change in the ground-state wave function of the system at $P_c$. Previous pressure work revealed that two energy scales, one associated with Kondo coherence and the other with crystalline electric field (CEF) splitting, become similar at $P_c$. As a result, wave functions of the excited crystal-field levels become admixed into the ground state, hindering formation of a fully Kondo coherent ground state, yet allowing new magnetic orders that lead to a magnetic state that persists to over 4 GPa [20]. Because of the competing magnetic interactions known to be present in the class of localized materials, various magnetic orders compete under pressure and magnetic field. The family member CeAgSb$_2$ also shows a new magnetic phase above $P_c \sim 2.7$ GPa, and $T_{\text{max}}$ exhibits unexpected negative pressure dependence above $P_c$, which may be due to the influence of a low-lying CEF level $\Delta_1 \sim 50$ K [44,54]. Neutron and x-ray scattering studies would be valuable to shed light not only on the crystal-field wave functions at ambient conditions but also on their evolution under applied pressure and magnetic fields.

V. CONCLUSIONS

In summary, we have constructed the temperature-magnetic-field phase diagrams of CeAuSb$_2$ under applied pressure. Bulk thermodynamic probes reveal two closely lying phase transitions at $T_N = 6.3$ K and $T_{\text{nem}} = 6.5$ K, and x-ray diffraction measurements verify that striped magnetic order is connected to a structural phase transition at ambient pressure. Our theoretical model suggests that stripe magnetic order is preceded by a nematic phase in CeAuSb$_2$. The discovery of a putative nematic phase in an $f$-electron material at zero magnetic field provides an unexplored framework for nematicity, though superconductivity, if present, remains to be discovered.

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