

Symmetric versus antisymmetric strain tuning of the valence transition in $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$

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Similar to transitions in a range of correlated quantum materials, the valence transition exhibits a strong coupling to the crystal lattice, rendering it highly sensitive to stress tuning. In the present work, we determine the effect of uniaxial stress, which breaks the lattice symmetry, on the valence transition temperature and its crossover temperature in pure and Ag-substituted YbInCu_4 . Our key result is that hydrostatic stress is more effective in tuning this transition than uniaxial stress. Based on a symmetry decomposition of the stress-induced strains, we argue that this observation can be quantitatively understood, given that the valence transition is mostly sensitive to symmetric strains and thus volume changes of the lattice. These results support the notion that the valence transition can give rise to critical elasticity close to its critical endpoint.

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I. INTRODUCTION

The strong coupling between electronic and lattice degrees of freedom in correlated quantum materials makes their electronic properties highly sensitive to external stress and strain. Likewise, the electronic system can exert a significant influence on the lattice response. Importantly, this influence may go beyond a small, perturbative response. Rather than adhering to Hooke's law with a linear stress-strain relationship, these systems can show a strongly nonlinear lattice response, signaling a nonperturbative interaction between electrons and the crystal lattice.

Striking examples of such behavior include the breakdown of Hooke's law near the Mott transition in an organic conductor [1], the pronounced lattice softening accompanying the electronic Lifshitz transition in the unconventional superconductor Sr_2RuO_4 [2], and the significant renormalization of the Young's modulus observed at the nematic transition in iron-based superconductors [3].

Crucially, this strong electron-lattice coupling alters the fundamental nature of phase transitions in these systems. The long-range nature of the lattice forces acts to suppress electronic fluctuations, which in turn drives such transitions toward mean-field behavior. As a result, even though these transitions are driven by electronic degrees of freedom, the lattice also becomes critical and determines the universal behavior of the electronic transition. This phenomenon, known

as critical elasticity [4,5], has been experimentally confirmed at the Mott finite-temperature critical endpoint [1] and theoretically proposed to govern the behavior at nematic [6], metamagnetic [7], and altermagnetic [8] quantum critical points.

To experimentally establish the widespread relevance of critical elasticity in correlated-electron systems, it is essential to identify additional material realizations where the properties of the critical endpoints are experimentally accessible. Theoretically, the emergence of critical elasticity is governed by symmetry-allowed couplings between the electronic order parameter, Φ , and an appropriate lattice strain component, ε_{ij} [4,5,7]. Consequently, symmetry analysis provides a powerful framework to guide the search for additional candidate systems. In this context, it is noted that the valence transition in rare-earth compounds exhibits striking similarities to the Mott transition, suggesting it as a promising reference case.

The valence transition, at which the valence of a rare-earth ion changes, can be typically controlled either by temperature or by external parameters, such as chemical substitution or pressure. When the transition is induced at low temperatures, it is first order. This first-order transition line terminates in a finite-temperature second-order critical endpoint, above which only a crossover between the two valence states exists [see Fig. 1(a)]. Since the valence is a scalar order parameter Φ (like the electronic order parameter of the Mott transition), it can be expected that the electronic critical endpoint is governed by an emergent Ising symmetry. In this case, the symmetry of Φ allows a linear coupling to symmetry-conserving volumetric strains, ε_{A1g} [see Fig. 1(c)], of the form $\Phi\varepsilon_{ij}$ in the free energy [4,7]. This condition gives rise to critical elasticity, where the purely electronic critical endpoint is preempted by an isostructural solid-solid endpoint, characterized by a change in volume.

Indeed, the valence transition can in many systems be controlled by hydrostatic stress, σ_{hydro} , [11,12] consistent with the picture that the transition is primarily driven by volumetric

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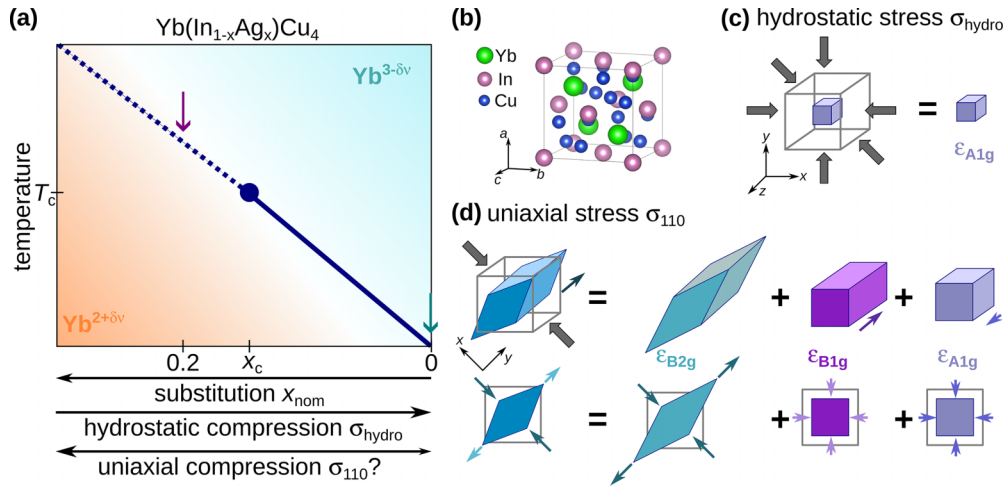


FIG. 1. (a) Schematic phase diagram for the valence transition from divalent to trivalent Yb in $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ as a function of temperature and external control parameters, such as substitution level, x , or hydrostatic stress, σ_{hydro} . At low temperatures, the transition is first order (solid line). The first-order transition ends in a second-order critical endpoint, which is located at $(x_{c,\text{nom}}/x_{c,\text{EDX}}, T_c) \approx (0.2/0.1, 75 \text{ K})$ [9]. Beyond the critical point, a broad crossover regime (dashed line) is observed. The focus of the present work is on two members of the family with $x = 0$ and $x_{\text{nom}} = 0.2/x_{\text{EDX}} = 0.126$, whose positions in the general phase diagram are marked by the teal and purple arrows. The phase diagram under uniaxial stress, $\sigma_{[110]}$, has not been explored yet and is accordingly marked by a question mark. (b) Schematic cubic crystal structure [10] of YbInCu_4 . (c), (d) Schematic illustration of the stress-induced strains in a cubic lattice for hydrostatic stress (c) and uniaxial stress (d). In each panel, the gray cube indicates the original cubic lattice and the bold gray arrows indicate the directions of applied stress. (c) Hydrostatic compression induces symmetry-preserving ϵ_{A1g} strains. (d) In contrast, applying uniaxial compression along the diagonal cubic axis $[110]$ breaks the lattice symmetry. Due to the crystal's Poisson ratio, the induced longitudinal and transverse strains are different in magnitude along these three directions, as indicated by the different color of the small arrows. The induced strains can be described by a superposition of irreducible strains of the point group of the crystal lattice: the fully antisymmetric B_{2g} and B_{1g} strains and a fully symmetric A_{1g} strain (for details, see text).

strains. However, given that the valence transition is believed to originate from the interaction between the f electrons and the conduction (c) electrons [13], which can in principle be anisotropic, it is possible that the transition can also be controlled by symmetry-breaking anisotropic strains [14], ϵ_{B2g} and ϵ_{B1g} [see Fig. 1(d)]. The latter are induced by applying uniaxial stress.

In the present work, we report on the phase diagram of the valence transition under uniaxial stress in the series of cubic $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ [see Fig. 1(b)]. The pure compound undergoes a first-order valence transition [13] as a function of temperature at $T_V \approx 42 \text{ K}$, at which the valence changes from the smaller $\text{Yb}^{2.9+}$ to the larger $\text{Yb}^{2.7+}$ upon cooling [15,16]. Correspondingly, the transition is accompanied by an increase of volume of 0.5 % without experimentally detectable changes in crystalline symmetry [10,17]. Tuning the valence transition was achieved in various substitution studies (e.g., in Refs. [9,18–21]). In those that report on $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ [9,16,18,22,23], it was established that the first-order transition line moves to higher temperatures and terminates in a second-order critical endpoint, above which only a crossover between the two valence states exists. Recent systematic studies of substituted samples [9] revealed that the critical endpoint is located close to $(x_{c,\text{nom}}/x_{c,\text{EDX}}, T_c) \approx (0.2/0.1, 75 \text{ K})$ [with x_{nom} (x_{EDX}) the nominal (actual) concentration]. Similarly, the phase diagram has been explored using hydrostatic stress [24–26]. Since hydrostatic compression [see Fig. 1(d)] favors the smaller trivalent state, it generally suppresses the transition temperature T_V and the crossover temperature T'_V [see Fig. 1(a)]. No experimental signatures

for a change of the cubic symmetry were observed based on powder x-ray diffraction in the substituted samples [9].

However, various unusual aspects of the valence transition in YbInCu_4 were noted, which may indicate the need to investigate the effects of symmetry-breaking pressures.

First, the origin and the key drivers of the transition remain under debate. It was pointed out early on that the small change of the volume is insufficient to explain the apparent large change of the Kondo temperature from $\approx 20 \text{ K}$ to $\approx 400 \text{ K}$ observed across the valence transition [27]. While recent electronic-structure studies attributed this to an unusual modification of the bare band structure in the presence of $c-f$ hybridization [28,29], other experiments have questioned the strength or even the presence of such hybridization [30]. If Kondo physics is indeed involved, a strong increase in the Kondo temperature could arise from enhanced anisotropy in the $c-f$ hybridization and/or from the splitting of the crystalline electric field (CEF) levels. In that case, the transition and its properties are expected to be sensitive to symmetry-breaking strain. Finally, geometric frustration of the Yb sublattice [19] has also been suggested to influence the transition, an effect that could likewise be tuned by symmetry-breaking strain.

Second, the notion of an isostructural transition may be questioned by ultrasonic investigations which revealed step-like anomalies in the transverse elastic moduli, $(c_{11} - c_{12})/2$ and c_{44} , at T_V and T'_V in pure and substituted compounds, respectively. Such anomalies are forbidden on symmetry grounds for an isostructural transition and therefore may indicate a crystalline symmetry-breaking at the transition [14,31].

TABLE I. Summary of samples investigated in the present study. Following the description of the sample characterization in Ref. [9], we denote the nominal x value and the x value determined by EDX. We also note the transition temperature T_V or the crossover temperature T'_V at ambient stress, determined from a piece of the crystal used in the present work. Finally, dimensions of necked samples, used in the present study, which were cut and measured with a Xenon Plasma Focused Ion Beam (PFIB), are provided.

x_{nom}	x_{EDX}	T_V or T'_V (K)	length (μm)	width (μm)	thickness (μm)
0	0	44.4 ± 0.5	732	81	136
0.2	0.126 ± 0.01	87.0 ± 0.5	501	102	125

The latter result motivates our study to explicitly investigate the influence of symmetry-breaking strains on the valence transition. In particular, by applying uniaxial stress along the cubic $[1\ 1\ 0]$ direction, we generate both B_{1g} and B_{2g} strain components [see Fig. 1(d)], corresponding precisely to the distortions probed by the two transverse elastic modes. Depending on whether such spontaneous distortions are indeed present at the transition, the resulting phase diagram under uniaxial pressure is expected to exhibit distinct behavior from those under hydrostatic pressure.

In our experiments, we find that uniaxial stress along the cubic $[1\ 1\ 0]$ axis is less effective in tuning the valence transition and crossover temperature, T_V and T'_V , in $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ compared to hydrostatic stress [9,13,24,25,32]. Using an approach similar to the one developed in Ref. [33] for an iron-based superconductor, we use this data to disentangle the effects of symmetry-breaking and symmetry-conserving strains on T_V and T'_V . The key result of this analysis is that the transition is essentially only tuned by the symmetry-preserving ε_{A1g} strains, which are much smaller per stress unit in a uniaxial-stress experiment. Our results therefore support the notion that the valence transition is only controlled by changes in the volume and therefore its critical endpoint should be characterized by critical elasticity [5,34].

II. METHODS

The single crystals of $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ were grown following the procedure described in Ref. [9] with an initial melt composition of 1-1.76-5. Detailed information on the studied samples, their Ag concentration, and their ambient-stress properties are given in Table I. The ambient-stress transition and crossover temperatures, T_V and T'_V , were determined through measurements of the magnetization in a Quantum Design MPMS. In the ambient-pressure study reported in Ref. [9], specific-heat measurements were performed on crystals grown from the same initial melt. For the sample with $x_{\text{nom}} = 0$ and T_V identical to ours, a clear latent heat at the transition was observed, whereas no latent heat—consistent with a crossover—was detected for $x_{\text{nom}} = 0.2$ and a comparable T'_V . The EDX value for the substituted sample was determined for the exact piece of crystal studied under uniaxial pressure.

In general, the properties of substituted YbInCu_4 are very sensitive to structural and site disorder [17]. Importantly, the refinement of site occupancy factors for these samples, as reported in Ref. [9], revealed full occupancy of both the Yb and Cu sites. This finding indicates that Ag indeed substitutes on the In site, as suggested by the chemical formula. Nevertheless, the transition features become increasingly broadened

with higher x_{nom} and x_{EDX} , suggesting the presence of a certain degree of residual disorder in the actual materials. As the primary focus of this work is on the response of $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ to pressure, the conclusions presented here are, to a good approximation, not significantly influenced by the presence of disorder.

To study the response to uniaxial stress, we used *in situ*-tunable piezo-driven uniaxial stress cells, similar in design to the one reported in Ref. [35]. To this end, the single crystals were polished using a Xenon Plasma Focused Ion Beam (PFIB) into a dumbbell shape with a small neck, which will experience the stress, and larger tabs, which remain essentially unstrained [see Ref. [2] and inset of Fig. 2(a)]. The dimensions of the neck are given in Table I, with the long axis being the crystallographic $[1\ 1\ 0]$ axis, i.e., the axis of applied force. Throughout this work, we denote compressive stresses and strains with a negative sign.

To track T_V and T'_V as a function of $\sigma_{[110]}$, we measure the T - and $\sigma_{[110]}$ -dependent Young's modulus, $E_{[110]} = d\sigma_{[110]}/d\varepsilon_{[110]}$, with $\varepsilon_{[110]}$ being the induced strain along the stress direction. The methods to measure $E_{[110]}$ in piezo-driven uniaxial stress cells are described in Refs. [2] and [36]. In both methods, the extraction of absolute values of $E_{[110]}$ currently relies on an independent calibration at zero strain/stress, e.g., through ultrasonic measurements of the components of the elastic tensor, C_{ij} . Thus, the data presented in this paper are scaled such that they match Young's modulus obtained from the ultrasonic data of samples with similar composition, reported in Ref. [14]. Whereas this data can be used to track T_V and T'_V , caution should be taken when considering the absolute values of $E_{[110]}$, reported in this work.

III. RESULTS

We first discuss data on a pure sample of YbInCu_4 . Our precharacterization at ambient stress of the sample used in our study revealed that a first-order transition occurs at $T_V \approx (44.4 \pm 0.5)\text{K}$. Early ultrasonic measurements [14] on a sample of YbInCu_4 , grown using a slightly different method and with slightly different T_V , suggest a steplike change of $E_{[110]}$ at T_V [see gray line in Fig. 2(a)], consistent with the notion of a first-order transition. As shown in Fig. 2(a), where we display $E_{[110]}$ vs T at different negative $\sigma_{[110]}$, we find that the steplike anomaly at T_V shifts to lower temperatures with increasing compression. To extract T_V , we fit the experimental data by a broadened step function (see dashed lines) and assign the midpoint of the step to T_V . The resulting phase diagram of T_V vs $\sigma_{[110]}$ is shown in Fig. 2(b). The data is well described by a linear behavior with a slope of $dT_V/d\sigma_{[110]} = (6.4 \pm 0.5)\text{K/GPa}$.

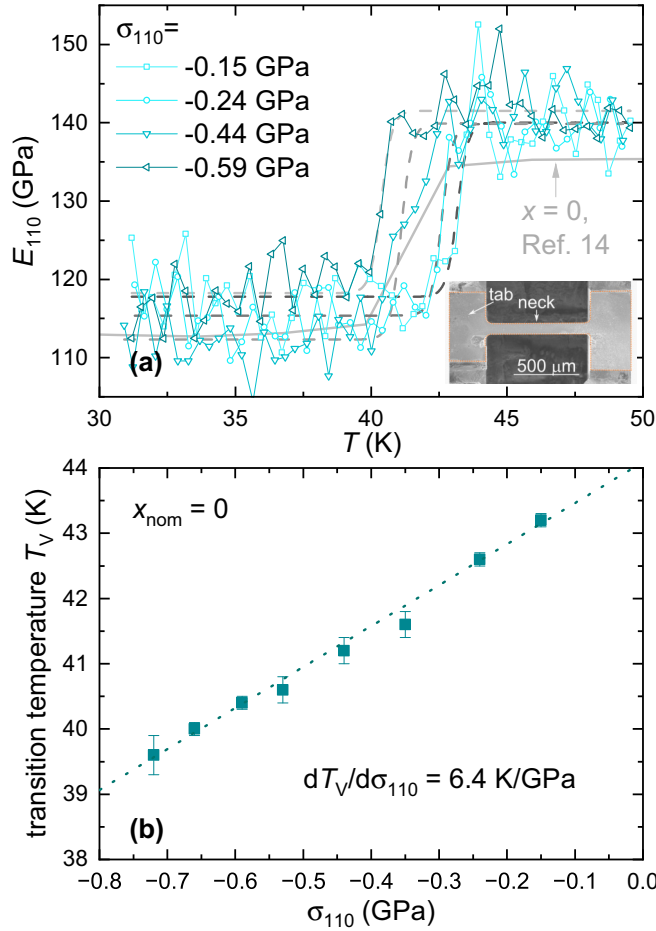


FIG. 2. (a) Young's modulus, $E_{[110]}$, of YbInCu_4 as a function temperature, T , under different uniaxial stress, $\sigma_{[110]}$ (negative sign denotes compression). The dashed lines represent fits to the data with a broadened step function to extract the valence transition temperature, T_V . The solid gray line represents the Young's modulus calculated from ultrasonic data from Ref. [14]. The inset shows a SEM image of the PFIB-cut sample used for this study. (b) T_V as a function of $\sigma_{[110]}$. The dotted line represents a linear fit to the experimental data.

Next we discuss the results for a sample of $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ with $x_{\text{nom}} = 0.2/x_{\text{EDX}} = 0.126$. At ambient stress, this sample undergoes a valence crossover at a characteristic temperature, $T'_V = (87.0 \pm 0.5) \text{ K}$. This crossover manifests itself in a broad minimum in the T -dependent $E_{[110]}$, as evident from the earlier ultrasound results [14] at ambient stress as well as our data at finite $\sigma_{[110]}$ [see Fig. 3(a)]. The different shape of the feature in $E_{[110]}$, compared to the steplike anomaly seen for $x_{\text{nom}} = 0$, highlights the change in the nature of the transition clearer than earlier heat-capacity measurements [9]. This provides an important confirmation of the previous assignment of the respective features to a phase transition for $x_{\text{nom}} = 0$ and a crossover for $x_{\text{nom}} = 0.2/x_{\text{EDX}} = 0.126$. Similarly to the previous results on the unsubstituted compound, T'_V decreases with increasing compression. We determine T'_V as the minimum in $E_{[110]}(T)$ and plot T'_V as a function of $\sigma_{[110]}$ in

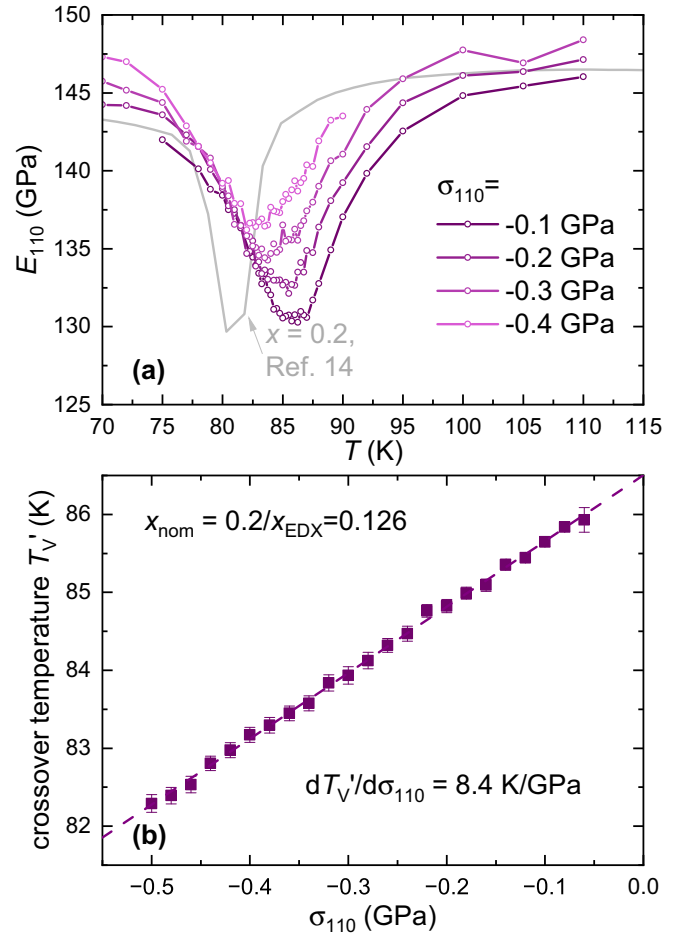


FIG. 3. (a) Young's modulus, $E_{[110]}$, of $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ ($x_{\text{nom}} = 0.2/x_{\text{EDX}} = 0.126$) as a function temperature, T , under different uniaxial stress, $\sigma_{[110]}$ (negative sign denotes compression). The crossover temperature, T'_V , was determined from the minimum of the $E_{[110]}(T)$ curves. The gray line represents the Young's modulus calculated from ultrasonic data from Ref. [14]. (b) T'_V as a function of $\sigma_{[110]}$. The dotted line represents a linear fit to the experimental data.

Fig. 3(b). The stress dependence is well described by a linear behavior with a slope of $dT'_V/d\sigma_{[110]} = (8.4 \pm 0.5) \text{ K/GPa}$.

IV. DISCUSSION

The key experimental result of our work is that T_V and T'_V are suppressed linearly with compressive $\sigma_{[110]}$. This result may be surprising in light of the sizable antisymmetric B_{1g} and B_{2g} strains in our uniaxial-stress experiment. In general, since the transition temperature, T_V , and crossover temperature, T'_V , have to be invariant under the symmetry operations of the point group of the crystal (here, among others, the C_4 rotation of the cubic lattice), symmetry-breaking strains can only affect the transition and crossover temperatures in even powers, i.e., $\partial T_V/\partial \varepsilon_{B_{1g}} = \partial T_V/\partial \varepsilon_{B_{2g}} = 0$ and $\partial T'_V/\partial \varepsilon_{B_{1g}} = \partial T'_V/\partial \varepsilon_{B_{2g}} = 0$. However, symmetry-conserving $\varepsilon_{A_{1g}}$ strains can change the ordering temperature linearly. Thus, we assign the linear $T_V(\sigma_{[110]})$ and $T'_V(\sigma_{[110]})$ behavior, observed in this work, to the response to A_{1g} strains.

To support this conclusion on a quantitative level, we compare our results to those obtained under hydrostatic stress. To compare the data, we need to explicitly calculate the magnitude of irreducible strains induced in hydrostatic and uniaxial stress experiments [see Figs. 1(c) and 1(d)]. To this end, we use the elastic compliance tensor S_{ij} for a cubic lattice [37], which is defined in the basis of the crystallographic axes and reprinted in Appendix Eq. (A1).

In a hydrostatic stress experiment [see Fig. 1(c)], $\sigma_{11} = \sigma_{22} = \sigma_{33} = \sigma_{\text{hydro}}$ are finite and all other components zero. Correspondingly, this stress causes all three cubic directions to shrink equally ($\varepsilon_{11} = \varepsilon_{22} = \varepsilon_{33}$) and the deformation can therefore be described by a fully symmetric A_{1g} strain only. Using the definition $\varepsilon_{A_{1g}} = \frac{1}{3}(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33})$ is then given by

$$\varepsilon_{A_{1g}} = \frac{1}{(C_{11} + 2C_{12})} \sigma_{\text{hydro}}. \quad (1)$$

When uniaxial stress is applied along the crystallographic $[110]$ direction, the lattice symmetry is broken. While the crystal is compressed along the $[110]$, it expands along the $[1-10]$ and $[001]$ directions [see small arrows in Fig. 1(d)]. To describe the deformations, we need to consider a rotated coordinate system in which the x and y axes are aligned along $[110]$ and $[1-10]$, respectively. The rotated compliance matrix, S'_{ij} , is given in Appendix Eq. (A1). In this frame, the only component of the stress tensor that is finite is $\sigma_{11} = \sigma_{[110]}$. Correspondingly, the strains read as $\varepsilon_{11} = S'_{11}\sigma_{[110]}$ (along the $[110]$ direction), $\varepsilon_{22} = S'_{12}\sigma_{[110]}$ (along the $[1-10]$ direction), and $\varepsilon_{33} = S'_{13}\sigma_{[110]}$ (along the $[001]$ direction). Thus, the crystal strain is different along the x , y , and z directions. Therefore, in total three irreducible strains are needed to describe the induced deformation [see Fig. 1(d)]. This includes the fully antisymmetric in-plane shear distortion, $\varepsilon_{B_{2g}} = \frac{1}{2}(\varepsilon_{11} - \varepsilon_{22})$, the tetragonal out-of-plane distortion, $\varepsilon_{B_{1g}} = \frac{1}{3}(\varepsilon_{33} - (\varepsilon_{11} + \varepsilon_{22}))$, as well as the volumetric $\varepsilon_{A_{1g}}$, defined above. Figure 1(d) illustrates the induced irreducible strains, shown from a three-dimensional perspective (top) and as a projection onto the x - y plane (bottom). Inserting the explicit expressions for S'_{ij} yields

$$\varepsilon_{B_{2g}} = \frac{1}{4C_{44}} \sigma_{[110]}, \quad (2)$$

$$\varepsilon_{B_{1g}} = - \frac{C_{11} + C_{12}}{3(C_{11}^2 + C_{11}C_{12} - 2C_{12}^2)} \sigma_{[110]}, \quad (3)$$

$$\varepsilon_{A_{1g}} = \frac{1}{3(C_{11} + 2C_{12})} \sigma_{[110]}. \quad (4)$$

Direct comparison of Eqs. (1) and (4) shows that the amount of A_{1g} strain induced in a uniaxial-stress experiment is only a third of the one induced in a hydrostatic-stress experiment. Thus, if the stress dependence of T_V and T'_V is solely attributed to the A_{1g} response, then $dT_V/d\sigma_{\text{hydro}} = 3dT_V/d\sigma_{[110]}$ and $dT'_V/d\sigma_{\text{hydro}} = 3dT'_V/d\sigma_{[110]}$. For the pure compound ($x = 0$), our results of $dT_V/d\sigma_{[110]} = (6.4 \pm 0.5) \text{ K/GPa}$ match the expectations of a purely A_{1g} -driven response, since $dT_V/d\sigma_{\text{hydro}} = (18 \pm 2) \text{ K/GPa}$, where the error bar reflects the spread of reported values in different studies [13,24,25,32]. Similarly, for the Ag-substituted $x_{\text{nom}} = 0.2/x_{\text{EDX}} = 0.126$ sample, we find $dT'_V/d\sigma_{[110]} =$

$(8.4 \pm 0.5) \text{ K/GPa}$, which is very close to one-third of the $dT'_V/d\sigma_{\text{hydro}} = 25 \text{ K/GPa}$, recently reported in Ref. [9].

The analysis above suggests that the valence transition in the $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ family is essentially unaffected by antisymmetric B_{1g} and B_{2g} strains. Overall, the finding that the valence transition is mostly tuned by A_{1g} strains is consistent with the picture that the valence transition is an isostructural phase transition. The critical endpoint of such a transition is predicted to show critical elasticity [34], which should experimentally manifest itself in a critically diverging compressibility $\kappa = 3/(C_{11} + 2C_{12})$ (or in other words, a vanishing bulk modulus $B = \kappa^{-1}$). Since the experimentally studied $E_{[110]}$ in the present work involves a combination of C_{11} , C_{12} , and C_{44} [see Eq. (A5)], a precise determination of the bulk modulus near the critical endpoint would require directional-dependent measurements to disentangle these contributions. Such an investigation lies beyond the scope of the present study. Nevertheless, for such an analysis to be meaningful, it remains to be understood why the transverse elastic constants $(C_{11} - C_{12})/2$ and C_{44} exhibit step-like anomalies at the valence transition, despite these being symmetry-forbidden in case of an isostructural transition. Together with the absence of a measurable response of T_V and T'_V to antisymmetric $\varepsilon_{B_{2g}}$ and $\varepsilon_{B_{1g}}$ strains, we speculate that these anomalies in the transverse modes are of extrinsic origin [38]. A pronounced sample-to-sample variation in the jump sizes of $C_{11} - C_{12}$ and C_{44} (cf. Refs. [14] and [31]) at both the transition and crossover supports this scenario. Further studies on the role of disorder and its coupling to elastic degrees of freedom near the critical endpoint [1,39] will be crucial to resolve these questions [38].

Notably, even though the valence transition is generally less sensitive to symmetry-breaking strains than to symmetry-preserving strains, uniaxial stress can still be used to control the transition due to the non-negligible symmetric A_{1g} strain that is induced in the experiment. The controllability by uniaxial stress offers the perspective to study its properties by surface-sensitive measurements [40,41], which cannot be conducted in the constraining environment of a hydrostatic stress cell.

V. CONCLUSION

In this work, we studied the temperature-uniaxial stress phase diagram of the valence transition in $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$. To this end, we studied a sample with $x = 0$, which undergoes a first-order valence transition as a function of temperature, and a sample with $x_{\text{nom}} = 0.2/x_{\text{EDX}} = 0.126$, for which a valence crossover occurs as a function of temperature. We observe a linear suppression of the valence transition temperature, T_V , and the crossover temperature, T'_V , with uniaxial stress applied along the crystallographic $[110]$ direction, $\sigma_{[110]}$. Based on a quantitative calculation of the stress-induced strains, we show that $dT_V/d\sigma_{[110]}$ and $dT'_V/d\sigma_{[110]}$ can be fully accounted for by the response of T_V and T'_V to symmetry-conserving A_{1g} strains, as deduced from hydrostatic stress experiments. As a result, T_V and T'_V are essentially insensitive to symmetry-breaking B_{1g} and B_{2g} strains. The findings of this study are consistent with the picture that the valence transition is solely driven by volumetric effects. As

a result, the valence transition in $\text{Yb}(\text{In}_{1-x}\text{Ag}_x)\text{Cu}_4$ fulfills the symmetry conditions [4,5,7] for which the occurrence of critical elasticity has been predicted.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [42].

APPENDIX

1. Rotation of the compliance matrix

The compliance matrix $S_{ij} = (C_{ij})^{-1}$ (i.e., the inverse of the elastic constant matrix C_{ij}) of a cubic crystal in Voigt notation is given by

$$\begin{pmatrix} \frac{C_{11} + C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & -\frac{C_{12}}{C_{11} + C_{12}} & -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & 0 & 0 & 0 \\ -\frac{C_{12}}{C_{11} + C_{12}} & \frac{C_{11}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & -\frac{C_{12}}{C_{11} + C_{12}} & 0 & 0 & 0 \\ -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & -\frac{C_{12}}{C_{11} + C_{12}} & \frac{C_{11}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_{44}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{C_{44}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{C_{44}} \end{pmatrix}. \quad (\text{A1})$$

To calculate the induced strains when applying stress along the $[1\ 1\ 0]$ crystallographic direction, the compliance matrix needs to be expressed in terms of a basis where the two in-plane directions are oriented along $[1\ 1\ 0]$ and $[1\ -1\ 0]$. To obtain the compliance matrix in this basis, S'_{ij} , we rotate S_{ij} by 45° using $t_\varepsilon S t_\sigma^{-1}$, with

$$t_\varepsilon = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & -\frac{1}{2} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad (\text{A2})$$

$$t_\sigma^{-1} = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & -1 \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 & 0 \end{pmatrix}. \quad (\text{A3})$$

The result for S'_{ij} reads as

$$\begin{pmatrix} \frac{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2 + 2C_{11}C_{44}}{4C_{11}^2C_{44} + 4C_{11}C_{12}C_{44} - 8C_{12}^2C_{44}} & -\frac{C_{12}^2 + C_{11}C_{12} - 2C_{12}^2 - 2C_{11}C_{44}}{4C_{11}^2C_{44} + 4C_{11}C_{12}C_{44} - 8C_{12}^2C_{44}} & -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & 0 & 0 & 0 \\ -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & \frac{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2 + 2C_{11}C_{44}}{4C_{11}^2C_{44} + 4C_{11}C_{12}C_{44} - 8C_{12}^2C_{44}} & -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & 0 & 0 & 0 \\ -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & -\frac{C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & \frac{C_{11} + C_{12}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_{44}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{C_{44}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{2}{C_{11} - C_{12}} \end{pmatrix}. \quad (\text{A4})$$

Correspondingly, the Young's modulus, $E_{[110]}$, is given by

$$E_{[110]} = (S'_{11})^{-1} = \frac{4C_{11}^2C_{44} + 4C_{11}C_{12}C_{44} - 8C_{12}^2C_{44}}{C_{11}^2 + C_{11}C_{12} - 2C_{12}^2 + 2C_{11}C_{44}}. \quad (\text{A5})$$

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