Electronic Landscape of the f-electron Intermetallics with the $ThCr_2Si_2$ Structure

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Although strongly correlated f-electron systems are well known as reservoirs for quantum phenomena, a persistent challenge is to design specific states. What is often missing are simple ways to determine whether a given compound can be expected to exhibit certain behaviors and what tuning vector(s) would be useful to select the ground state. In this review, we address this question by aggregating information about Ce, Eu, Yb, and U compounds with the $ThCr_2Si_2$ structure. We construct electronic/magnetic state maps that are parameterized in terms of unit cell volumes and d-shell filling, which reveals useful trends including that (i) the magnetic and nonmagnetic examples are well separated, and (ii) the crossover regions harbor the examples with novel states. These insights are used to propose structural/chemical regions of interest in these and related materials, with the goal of accelerating discovery of the next generation of f-electron quantum materials.

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I. INTRODUCTION

Interest in strongly correlated f-electron intermetallics is periodically renewed by discoveries of exemplary materials with truly unique behaviors (e.g., hidden order and superconductivity in URu_2Si_2, [1] anomalously high temperature superconductivity in $PuCoGa_5$, [2] topological insulating behavior in SmB_6 [3], strongly correlated Weyl-Kondo semimetallic behavior in Ce-based compounds, [4] and heavy fermion superconductivity in many Ce- and U-based systems, [5, 6]). The vitality of this cycle was recently seen in the emergence of unconventional spin triplet superconductivity in UTe_2, [7, 8] which features anomalously large upper critical fields and magnetic field driven reentrant superconductivity. Even amongst the heavily studied variants of the $ThCr_2Si_2$ structure, this trend towards serendipitous discovery is alive and well. For example, $CeRh_2As_2$ ($CaBe_2Ge_2$-type structure) was recently shown to exhibit unconventional superconductivity, anomalously large upper critical fields, and evidence for several superconducting order parameters. [9, 10] Both of these materials may even feature nontrivial electronic topologies.

These types of discoveries clearly invite continued efforts to develop f-electron intermetallics, but the field is hampered by a lack of clarity regarding where to look for examples with enhanced properties. This is largely because (i) the relative strengths of interactions (e.g., Kondo, RKKY, valence instability, spin orbit, crystal electric field splitting, etc.) vary widely between different materials, (ii) unusual states often emerge as a result of finely balanced or cumulative interactions, and (iii) calculations to quantify the relative importance of different interactions often have limited success. Historically, this has necessitated systematic experimental surveys of the chemical/structural phase space to uncover materials with novel electronic and magnetic states. [11] However, it is also widely held that these resource intensive surveys are not optimal - at least in the sense that the discovery of examples with remarkable physics requires sifting through a large number of related examples, most of which show conventional behavior that fails to drive the field forward.

What is often missing in this process is a simple way to determine whether a given compound can reasonably be expected to exhibit novel behavior (either intrinsically or under modest tuning) and what tuning vector(s) would be useful. Herein, we address this challenge by reexamining the families of materials with the AT_2X_2 composition [12, 13], where we show that for the A = Ce, Eu, Yb, and U-based subsets with the $ThCr_2Si_2$-type structure, (i) the magnetic and nonmagnetic examples are well separated, (ii) the crossover region that separates them follows a simple but nontrivial trajectory, and (iii) the crossover region hosts the examples that exhibit attractive behavior such as unconventional superconductivity and non-Fermi-liquid behavior. These observations are consistent with earlier organizing principles (e.g., the Doniach phase diagram [14], the Hill plot [15], and surveys of Ce and U based 122 compounds [16–18] that emphasize electronic hybridization strength), but have the benefit that (i) they clarify chemical strategies to search for new examples with novel behavior and and (ii) provide a concise summary of behaviors in this structural family. We also suggest that this approach is well suited to elementary data mining of electronic databases that can be used to investigate many other structural families.

II. STRUCTURE, CHEMISTRY, AND GENERIC PHASE DIAGRAMS

The $ThCr_2Si_2$ structure (Fig. 1a) was first reported by Ban and Sikirica in Ref. [12], and since then it has proven

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to be one of the most ubiquitous structural arrangements for ternary combinations of elements. There are many detailed reviews that address trends in this family, and several are listed in Ref. [13]. To summarize, it is a ternary variant of the $BaAl_4$ prototype (space group $I4/mmm$), and is generically expressed as AT_2X_2, where the A, T, and X atoms are located on the Wyckoff sites 2*a* (0,0,0), 4*d* (0,0.5,0.25), and 4*e* (0,0,z), respectively. This provides distinct high symmetry environments around the A, T, and X atoms which influence the physical properties of the chemical variants. This structure also exhibits pronounced chemical flexibility, where the A site can be populated by alkali metal, alkaline earth, rare earths, first column transition metals, lanthanide, and actinide elements, the T site can be occupied by transition metal, light alkali metals and alkaline earths, and p-block elements, and the X site can be occupied by p-block elements and some transition metals. Importantly, there are many other closely related structures (e.g., $CaBe_2Ge_2$-, $CeNiSi_2$-, $BaNiSn_3$-, and $U_2Co_3Si_5$-types [19–22]), and there even are hybrid examples that combine this family and other prototypes (Figs 1b-f) [23–25] which opens the prospect of developing design principles that span families of materials.

A multitude of behaviors emerge from these simple crystal structures when f-elements are introduced into them, including local moment and complex magnetism, [26] charge instabilities, [27] structural instabilities, [28] unconventional superconductivity, [29, 30] hidden order, [1] multipolar order, [31], and topologically protected electronic states, [9, 10]. For the Ce-, Yb-, and U based systems, the behavior is especially rich, and is often understood in terms of the Ruderman-Kittel-Kasuya-Yosida (RKKY) and Kondo interactions [14, 32–35], where (i) the RKKY interaction provides an indirect magnetic exchange between localized f-spins through the conduction electrons and favors magnetic ordering while (ii) the Kondo interaction drives hybridization between the conduction electron and f-states that results in screening of the f-spin and strongly reduces the effective magnetic moment. The connection between these parameters has been discussed extensively in terms of the Doniach model, and is summarized in Refs. [5, 6]. The resulting generic phase diagrams are shown schematically in Figs. 2a,b for Ce and Yb, where a tuning parameter δ (e.g., pressure or chemical substitution) varies the ground state. For the case of Ce, at small δ the valence is close to 3+, hybridization between the f- and conduction electrons is weak, and there typically is a magnetically ordered ground state at $T_{\mathrm{N,C}}$. As δ increases, $T_{\mathrm{N,C}}$ may initially increase as the RKKY interaction strengthens, but eventually it tends to be suppressed towards zero temperature at δ_c. Under some conditions, this results in a quantum critical point that is surrounded by a fan-like region of non-Fermi-liquid behavior. For many CeT_2X_2 compounds the quantum critical point is also surrounded by a dome of unconventional superconductivity. At larger δ the hybridization strength increases further, Fermi liquid behavior is observed below a crossover temperature T_{FL}, and eventually intermediate valence or a tetravalent state emerges. Importantly, the Ce and Yb phase diagrams are related, but are inverted with respect to each other owing to how Hund's rules determine the total angular momentum J: for Ce^{3+} ($J = 5/2$), Ce^{4+} ($J = 0$), whereas Yb 2+ ($J = 0$), and Yb 3+ ($J = 7/2$).

Some lanthanide and actinide based materials with multiple f-orbitals exhibit related phase diagrams, but additional complexities are involved. For example, a semi-universal phase diagram has been proposed for Eu-based intermetallics [36, 37], which resembles the Doniach picture but also includes distinct features relating to the valence transition between the Eu^{2+} ($J = 7/2$) and Eu^{3+} ($J = 0$) states (Fig. 2c). Interestingly, there is also an ongoing debate about the importance of valence instabilities in Ce and Yb based materials, their role in determining classes of quantum criticality, and impact on superconductivity [38–40]. We point out that related behavior might even be expected in families containing Pr, Sm, and Tm where multiple valence states are available. [41, 42] Amongst actinide based materials, the situation is even more complicated due to the greater tendency towards f-state itinerancy, the potential impact of relativistic effects, and the presence of multiple f-electron orbitals which could experience differing degrees of hybridization. [43] Nonetheless, phase diagrams that resemble those shown in Figs. 2a-c are sometimes observed [44, 45]. Finally, all of these behaviors should be contrasted with those of the remaining lanthanides, where (i) the valence is rigidly fixed to be trivalent and (ii) hybridization between the conduction electron and f-states is weak.

Based on these observations, it is appealing to suggest that although there are wide ranging behaviors in this family of materials, the QCP scenario provides a powerful design principle for producing examples with attractive behaviors. However, even with these insights, it remains unclear (i) which ones are best suited to further investigations because they are near a magnetic or valence instability and (ii) for a given material (or family of materials) what is the best tuning strategy to access regions of interest. In order to address this, we assemble maps in the chemical-structural phase space for the compounds (Ce,Yb,Eu,U)T_2X_2 with the $ThCr_2Si_2$ structure and identify regions of interest. We also comment on related structures and prospects for uncovering novel phenomena in them.

III. ELECTRONIC-MAGNETIC MAPS FOR (Ce,Yb,Eu,U)T_2X_2 WITH THE $ThCr_2Si_2$ STRUCTURE

Figure 3a presents the phase map for the compounds CeT_2X_2 (T = transition metal and X = Si,Ge) by providing the lattice constants and f-state as reported in literature [16–18, 29, 40, 46–69]. By organizing these

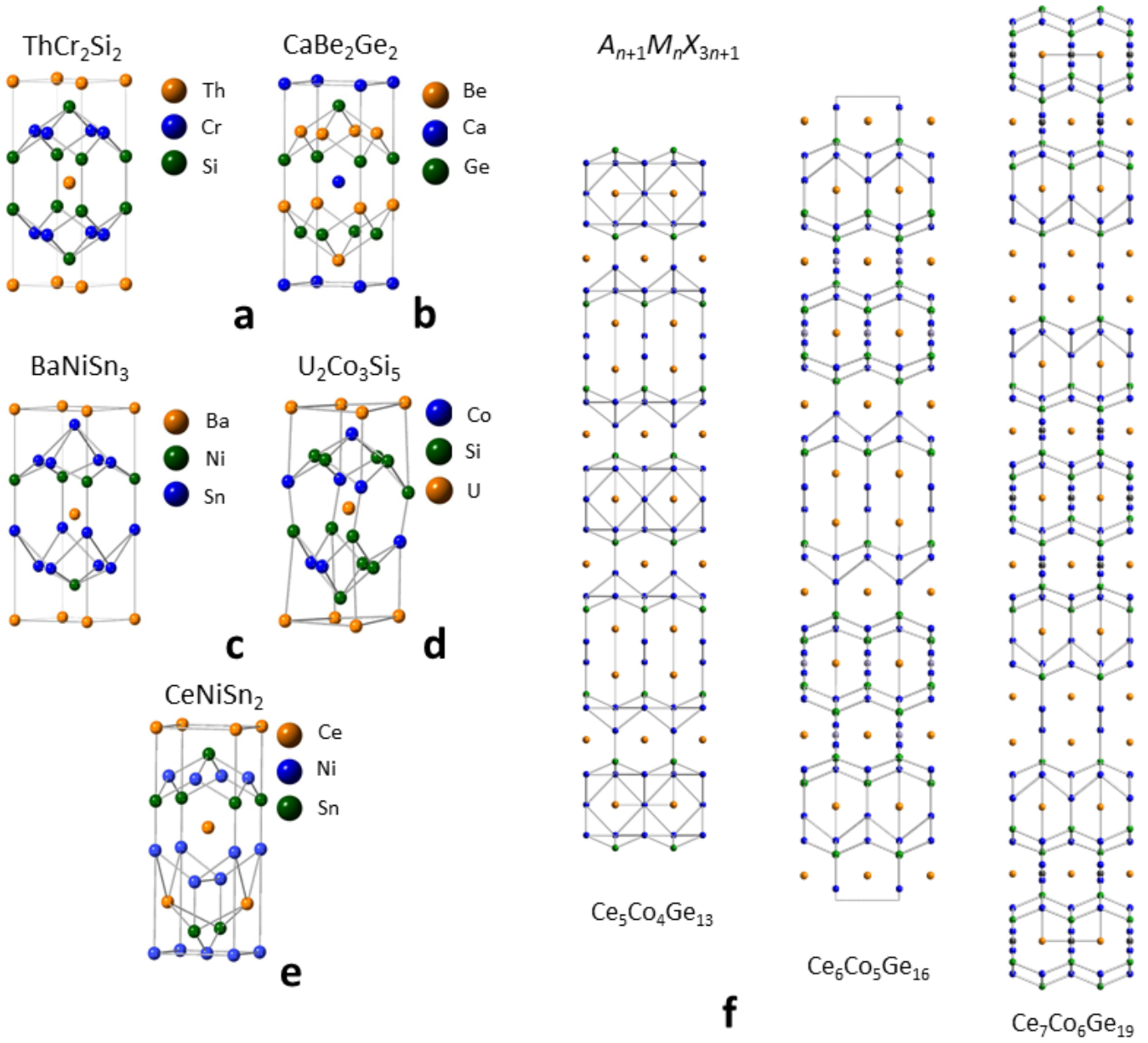

FIG. 1. **Summary of crystalline structures that relate to the $ThCr_2Si_2$ prototype** (a-e) The $ThCr_2Si_2$, $CaBe_2Ge_2$, $BaNiSn_3$, $U_2Co_3Si_5$, and $CeNiSi_2$, structures taken from Refs. [12, 13, 19–22]. (f) The structure for the $A_{n+1}M_nX_{3n+1}$ (A = lanthanide, M = transition metal, X = tetrels) n = 4-6 compounds, composed of complex layering of sub-units. Ce, Co, and Ge are represented as orange, green, and blue spheres. Structural details obtained from Ref. [23–25]

compounds based on their transition metal column and unit cell volume, it is seen that (i) there is a clear separation between those with trivalent Ce and tetravalent or intermediate valence Ce, (ii) the crossover region includes all of the examples that exhibit Kondo lattice heavy fermion, quantum criticality, non-Fermi-liquid, and superconducting behavior, and (iii) that the crossover region depends on a nearly linear relationship between shell filling and unit cell volume. Points (i) and (ii) are illustrated by the evolution from a strongly hybridized Kondo lattice ($CeCu_2Si_2$) towards weakened hybridization and strengthened magnetism as the unit cell volume increases. [29] This is also noticeable for the other isovalent transition metal series, which all go from tetravalent examples (e.g., $CeNi_2Si_2$ [61]) through strongly hybridized Kondo lattices (e.g., $CeNi_2Ge_2$ [60, 61]) to trivalent cerium magnetism ($CePd_2Ge_2$ [59, 60]). Supporting evidence for this evolution is seen by examining the unit cell volume lanthanide contractions for each family of materials, where reductions from the trivalent lan-

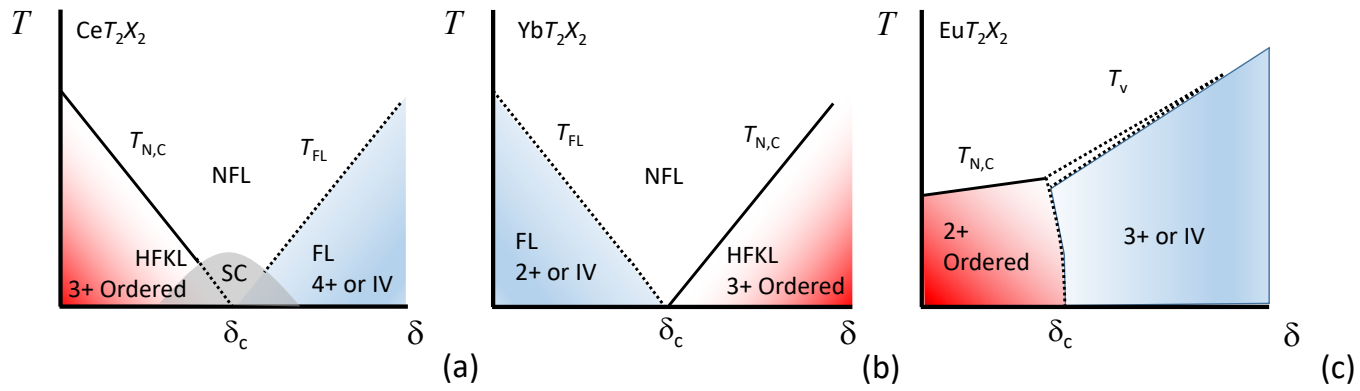

FIG. 2. **Schematic phase diagrams for strongly correlated f-electron intermetallics.** Temperature T vs. control parameter δ phase diagram for the compounds CeT_2X_2, [5, 6] YbT_2X_2, [5, 6] and EuT_2X_2 [36, 37], where T = transition metal and X = p-block element. Here, δ is the chemical composition x or pressure P. The trends for the magnetic ordering temperatures $T_{N,C}$, superconducting transition temperatures T_c, valence change transition temperatures T_V, and Fermi liquid crossovers T_{FL} that are observed in these phase diagrams are described in the text. The solid lines represent phase boundaries, whereas the dotted lines represent crossover regions: e.g., temperature ranges over which a system enters a Fermi liquid or intermediate valence (IV) ground state. The f-electron valences are also indicated (3+ or 4+ for cerium, 2+ or 3+ for ytterbium, and 2+ or 3+ for europium). Note that these diagrams focus on the critical regions near δ_c, but the more general Doniach phase diagram includes a region where the ordering temperatures increase with δ as the RKKY interaction strengthens, before collapsing towards $T = 0$ at δ_c [14]. This trend is seen in the ordering temperatures presented in Fig. 3.

thanide contraction are seen for tetravalent or intermediate valence examples. Related behavior is observed for many other cerium-based intermetallics, and is generally understood in the context of the Doniach picture or in terms empirical frameworks such as Hill plots (Fig. 2a). [6, 14, 15]

The effect of non-isoelectronic tuning is less easily anticipated, but is clarified by earlier studies showing that the hybridization strength between the f-electron and conduction electron states tends to decrease going from the iron column towards the copper column. [16–18]. Within the Ce-map, the importance of this is seen for the group of materials with unit cell volumes near 170 Å^3, where there is a progression from intermediate valence or tetravalent behavior ($CeOs_2Si_2$ [51]) to heavy fermion Kondo lattice behavior ($CeIr_2Si_2$ [56]), to quantum critical non Fermi liquid behavior and superconductivity ($CeNi_2Ge_2$ [60, 61]), and finally trivalent magnetic ordering ($CeCu_2(Si_{1-x}Ge_x)_2$ at $x \approx 0.2$ [66]). This illustrates that weakening hybridization causes the boundary between magnetic (Ce^{3+}) and nonmagnetic (Ce^{4+} or intermediate valence) behavior to shift towards smaller unit cell volumes with increasing d-shell filling. Outside of this crossover region, horizontal lines always traverse either intermediate valence or tetravalent cerium states (small volumes) or trivalent cerium states with magnetic ordering (large volumes).

Importantly, the examples that exhibit heavy Fermi liquid Kondo lattice behavior, superconductivity, or non-Fermi-liquid behavior (e.g., $CeRu_2Si_2$ [50], $CeCu_2Si_2$ [29] and $CeNi_2Ge_2$ [60, 61]) appear at the boundary between the two regions and are readily tuned through it by changing either the unit cell volume or the d-shell filling. For example, in the cases of $CeCu_2Si_2$ and $CeNi_2Ge_2$, applied pressure drives the ambient pressure superconducting transition through a dome-like region. [29, 60] Fermi liquid behavior that is consistent with the system entering either an intermediate valence or tetravalent cerium state emerges at large pressures, where a second dome of superconductivity is observed. In contrast, isoelectronic chemical substitution that expands the lattice drives these compounds into magnetic ground states where the hybridization strength is reduced. It is also seen that the examples with magnetically ordered ground states that are near the boundary (e.g., $CePd_2Si_2$ [60] and $CeRh_2Si_2$ [54]) are readily moved into it using applied pressure, while larger pressures are needed to move more distant examples (e.g., $CeAu_2Si_2$, [40] and $CeCu_2Ge_2$ [67]) into the crossover region. Non-isoelectronic chemical substitution series reveal related trends: e.g., when antiferromagnetic $Ce(Cu_{1-x}T_x)_2Ge_2$ ($x = 0$) is chemically substituted by T = Ni or Co the boundary region is crossed and critical behavior is observed over a limited x-range. [47, 69]

Thus, it is clear that for the entire $CeT_2(Si,Ge)_2$ series the region that separates the magnetic and nonmagnetic members varies systematically with both the unit cell volume and the electronic shell filling, which each tune the hybridization strength in a distinct way. This perspective is reinforced by considering the related maps for the compounds CeT_2X_2 (T = transition metal and X = P,As) (Fig. 3b) [70–77]. Although it is less clear in this case, we infer from these data and the trends that are seen for the Si/Ge analogues that there is a similar non-

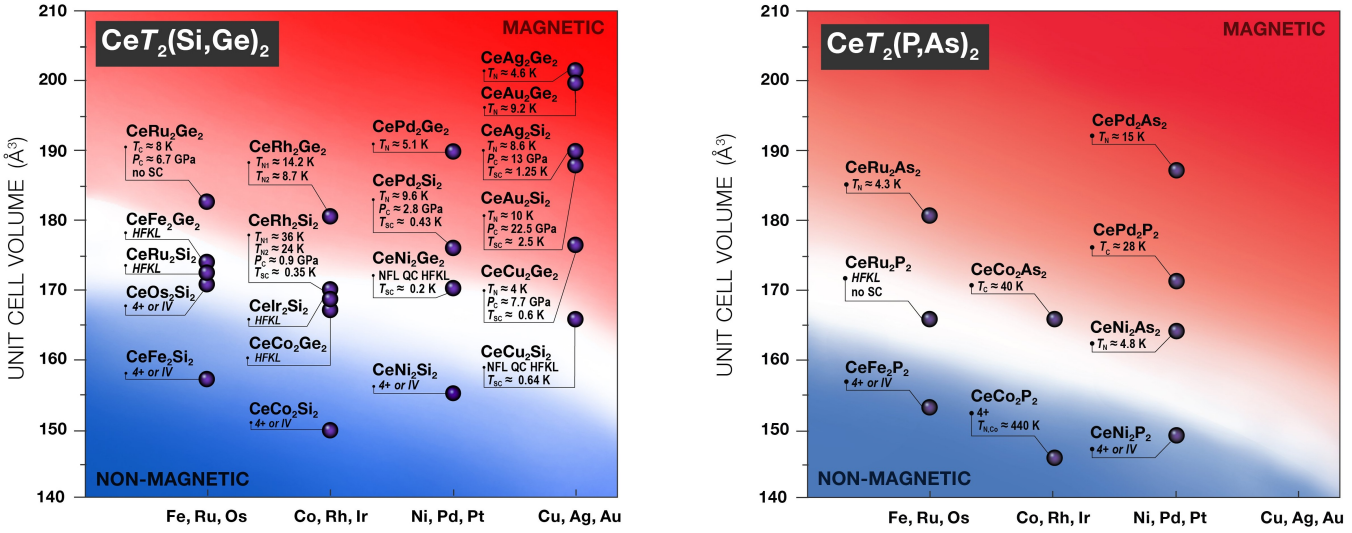

FIG. 3. **Phase map for the valence and ground state behavior of the compounds CeT_2X_2 (T = transition metal and X = Si/Ge and P/As) that crystallize in the ThCr$_2$Si$_2$-type structure. [16–18, 29, 40, 46–77].** The axes that control the ground state are the unit cell volume (V) and the d-shell filling going from the Cu column to the Fe column. The white band that traverses the center of the phase diagram is a guide to the eye that approximately separates the examples with tetravalent or intermediate valence cerium (lower left hand side (blue background)) from those with trivalent cerium (upper right hand side (red background)). Ordering temperatures are labeled (Neel temperature T_N and Curie temperature T_C). Also shown in some cases are the critical pressures where magnetism collapses (P_c) and the associated superconducting transition temperature (T_c). These values and their associated references are summarized in Table S1.

trivial vector separating the magnetic and nonmagnetic regions. As before, the examples that exhibit strongly correlated electron physics (e.g., CeRu$_2$P$_2$ [71]) are on the boundary.

Given the success of this simple scheme in describing the Ce based ThCr$_2$Si$_2$ compounds, we next examine the maps for the Yb examples (Fig. 4) [30, 31, 78–97]. Note that few pnictide analogues have been reported, so a map is not included. For the Si/Ge series, there is a strong resemblance between the Yb and Ce maps, but the magnetic and nonmagnetic regions are inverted. This is due to Hund's rules producing $J = 7/2$ for trivalent ytterbium ($4f^{13}$), while divalent Yb has a full f-shell ($4f^{14}$ and $J = 0$). In the intermediate volume region there are several nearly critical Kondo lattice systems, as well as the well-known quantum critical material YbRh$_2$Si$_2$ [30, 84]. Chemical substitution studies have been performed for many of these examples: e.g., (i) Rh $\rightarrow$ Co substitution in YbRh$_2$Si$_2$ stabilizes magnetism, weakens the hybridization strength, and leads to magnetic ordering [97], (ii) applied pressure drives YbFe$_2$Ge$_2$ from being a heavy fermion Kondo lattice through a quantum critical point with non-Fermi-liquid behavior, into an antiferromagnetically ordered ground state [80], and (iii) applied pressure drives divalent YbCu$_2$Ge$_2$ towards intermediate valence behavior [94]. Similar behavior is seen for tuning studies of other examples such as YbIr$_2$Si$_2$ [83], YbCu$_2$Si$_2$ [95], and YbPd$_2$Si$_2$ [96]. These observations suggest that the hybridization strength for the Yb compounds is strongly controlled by a combination of lattice contraction and d-shell filling in a manner that resembles what is seen for the Ce analogues.

It is also of interest to examine other Pr, Sm, Eu, and Tm based compounds that potentially could exhibit valence instabilities. [41, 42] Amongst this group, those with Pr, Sm, and Tm so far show no evidence in their bulk properties for crossover regions. This is supported by inspection of the evolution of their unit cell volumes, where all examples conform to the trivalent lanthanide contraction. This leads us to expect that although these families might, in principle, include interface regions they are not within the chemical phase space of the naturally occurring examples in this structure.

In contrast, the Eu compounds show trends that are related to the Ce- and Yb- analogues (Fig. 5) [36, 37, 98–131]. The compressed volume examples all exhibit either trivalent ($4f^6$, $J = 0$) or intermediate valence behavior while the expanded volume examples exhibit divalent ($4f^7$, $J = 7/2$) behavior. Examples close to the crossover region are readily tuned through it: e.g., the Eu valence and unit cell volume of EuCu$_2$Si$_2$ varies between 2+ and 3+ depending on synthesis method [115, 116] while EuIr$_2$Si$_2$ exhibits behavior that is similar to what is seen in Kondo lattice systems with modest hybridization strength [104]. When the antiferromagnets EuNi$_2$Ge$_2$ [108] and EuRh$_2$Si$_2$ [102] are compressed using hydrostatic pressure they evolve towards Kondo lattice-like behavior similar to that of EuIr$_2$Si$_2$. Remarkable behavior is seen for EuPd$_2$Si$_2$, which is nearly divalent at room temperature but its temperature dependent vol-

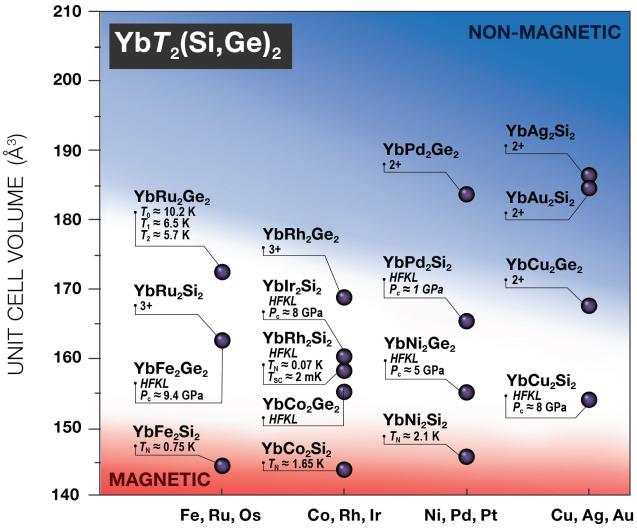

FIG. 4. **Phase map for the valence and ground state behavior of the compounds YbT_2X_2 (T = transition metal and X = Si/Ge) that crystallize in the ThCr$_2$Si$_2$-type structure [30, 31, 78–97].** The white band that traverses the center of the phase diagram is a guide to the eye that approximately separates the examples with trivalent (bottom (red background)) from those with divalent ytterbium (upper right hand side (blue background)). Ordering temperatures are labeled (Neel temperature T_N and Curie temperature T_C). Critical pressures P_c are labeled. These values and their associated references are summarized in Table S2.

ume contraction is sufficient to drive a phase transition into the trivalent state [36, 107]. Amongst the pnictides, it is noteworthy is that although most of them exhibit a divalent state, the heavy fermion Kondo lattice EuNi$_2$P$_2$ appears to be in a crossover region where the critical unit cell volume is substantially smaller than that of the Si/Ge analogues [130, 131]. These maps also reveal an important distinction from the Ce and Yb analogues, since here the electronic shell filling has a negligible impact on the location of the crossover region.

Finally, Fig. 6 summarizes results for the compounds UT_2X_2 [1, 79, 132–146]. There are a limited number of pnictide examples, so we focus on the Si/Ge group. Again there is a separation between the magnetic and nonmagnetic examples, but in this case the latter group are clustered around the Fe/Ru/Os transition metal group. Most of these compounds are Pauli paramagnets (e.g., UFe$_2$Si$_2$ [134], UFe$_2$Ge$_2$ [133], and UOs$_2$Si$_2$ [132]) where strong hybridization between the f- and conduction electron states causes the f-state to become delocalized. It is interesting to note that the hidden order compound, URu$_2$Si$_2$ is located in close vicinity to these examples, which is consistent with the view that strong hybridization plays an important role in this material [1]. Similar to what is seen for the lanthanides, the hybridization strength weakens going towards the Cu/Ag/Au column [16, 17]. The result is that the remainder of the compounds all exhibit magnetic ground states with large ordering temperatures. Some of these examples host complex magnetism (e.g., spin glass behavior in URh$_2$Ge$_2$ [135] and multiple phase transitions in many others) and are susceptible to disorder effects, but these behaviors do not appear to be associated with the crossover region. Decreases in the unit cell volume tend to slowly suppress the ordering temperature, but in contrast to the Ce, Yb, and Eu analogues there is no volume driven crossover region for this family. Instead large pressures are needed to access it, as demonstrated for UCo$_2$Si$_2$ which has a critical pressure near 8 GPa [140]. For UNi$_2$Si$_2$ and UCu$_2$Si$_2$ even larger pressures would be needed, as experiments have so far been unsuccessful in fully suppressing the magnetism [141, 146]. Thus it is clear that the U series is distinct from the Ce, Yb, and Eu analogues in terms of the conditions that would be useful for driving critical behavior. This has been remarked upon previously, [146] and likely reflects differences between the $5f$ and $4f$ states. Such information is of high importance in developing tuning strategies to access the critical region.

IV. OUTLOOK FOR FUTURE EFFORTS

These insights are immediately useful for focusing investigations of materials with the ThCr$_2$Si$_2$ structure. For example, although the Ce-series has already been extensively studied, there remain some attractive examples that have not received close attention. CeCo$_2$As$_2$ [73] is of interest because it is simultaneously near the crossover region and may also exhibit strong d-electron magnetism similar to what is seen for CeCo$_2$P$_2$. [74] Indeed, preliminary results reveal ferromagnetic ordering at $T_C \approx 40$ K [73], and we speculate that the ordered state would be readily suppressed using applied pressure, As $\rightarrow$ P substitution, or Co $\rightarrow$ Fe or Ni substitution. Examination of the Eu and Yb families reveals other opportunities. Both EuFe$_2$Ge$_2$ and EuRu$_2$Si$_2$ have not been reported, although the related compounds RFe$_2$Ge$_2$ (R = Y, Pr, Nd, Sm, Gd-Tm, Lu) and EuT_2Ge$_2$ (T = transition metal) are described in Refs. [147, 148]. Here it was inferred that EuFe$_2$Ge$_2$ is not a stable phase under conventional growth conditions. This leads us to propose that this phase, and others that are 'missing' from the maps, might be accessible as metastable phases where modest amounts of applied or chemical pressure might be sufficient to stabilize them. If they can be formed they might exhibit complex phase diagrams involving valence instability physics similar to what is seen in EuPd$_2$Si$_2$, [36, 107], EuRh$_2$Si$_2$ [102] or EuCo$_2$Ge$_2$, [103] where modest lattice contractions are sufficient to access the valence change region. The heavy fermion Kondo lattice EuNi$_2$P$_2$ appears to be within the crossover region and exhibits Kondo-lattice-like behavior [130, 131]. This invites efforts to traverse the crossover region using chem-

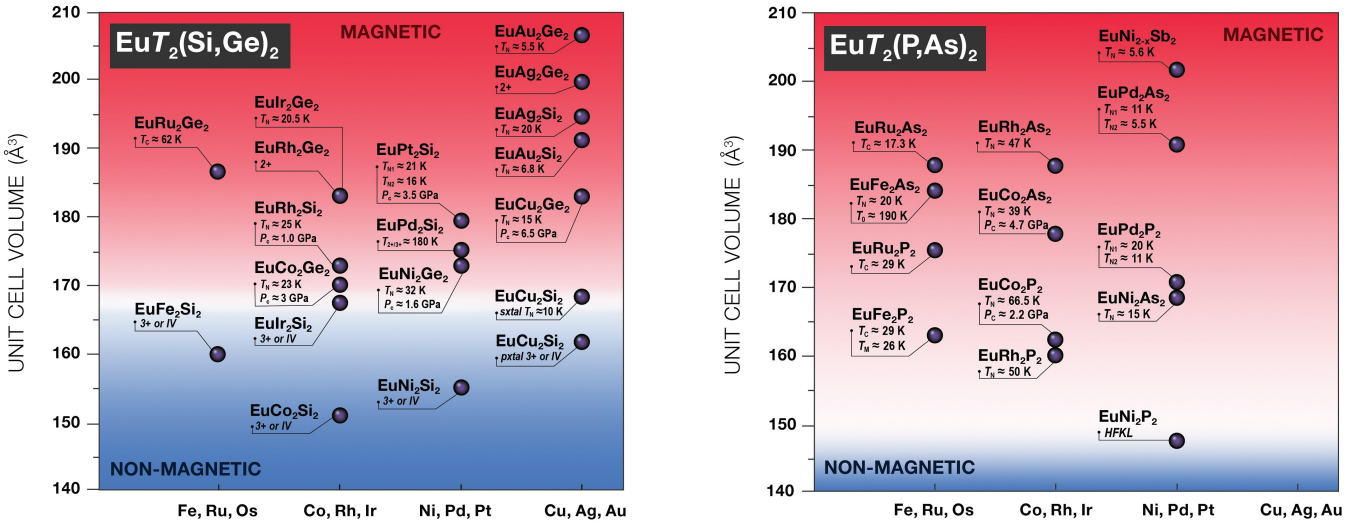

FIG. 5. **Phase map for the valence and ground state behavior of the compounds EuT_2X_2 (T = transition metal and X = Si/Ge and P/As) that crystallize in the $ThCr_2Si_2$-type structure [36, 37, 98–131].** The white band that traverses the center of the phase diagram is a guide to the eye that separates the examples with trivalent or intermediate valence europium (lower half (blue background)) from those with divalent europium (upper half (red background)). Ordering temperatures are labeled (Neel temperature T_N and Curie temperature T_C). Critical pressures P_c are labeled. These values and their associated references are summarized in Table S3.

ical substitution. Finally, for the Yb-based examples we note that there have already been substantial efforts, where the focus has been on the prototypical quantum critical point material $YbRh_2Si_2$. [30, 84] Nonetheless, there are several other remarkable materials in this family including $YbRu_2Ge_2$, [31] which exhibits quadrupolar order and strongly correlated electron behavior. This is unique amongst all other lanthanide based materials with the $ThCr_2Si_2$ structure and motivates chemical substitution studies that span the crossover region.

The U-based examples show distinct trends which draw attention towards d-shell filling as being the only viable route for entering the crossover region. This perspective has already been explored for URu_2Si_2, [149, 150] where electronic shell filling produces a semi-universal $T-x$ phase diagram with three main regions: (1) the hidden order state is rapidly suppressed towards zero temperature for $x \lesssim x_{cr,1}$, (2) paramagnetism with a heavy-Fermi-liquid ground state is seen for $x_{cr,1} \lesssim x \lesssim x_{cr,2}$, and (3) new types of complex antiferromagnetic order appears for $x_{cr,2} \lesssim x$. Surprisingly, this behavior is induced regardless of the type of chemical substitution (e.g., Ru $\rightarrow$ Rh, Ir and Si $\rightarrow$ P), as long as it effectively adds electrons. This motivates further studies of the nearby Pauli paramagnetic analogues, where non-isoelectronic chemical substitution can be used to tune towards the magnetic region (e.g., $U(Fe_{1-x}T_x)_2Ge_2$ where T = Co, Rh, Ir).

Finally, it will be valuable to use these insights to cast a wider net into the structural variants with the $CaBe_2Ge_2$-, $CeNiSi_2$-, $BaNiSn_3$-, and $U_2Co_3Si_5$- structure types, where a preliminary survey indicates that they exhibit maps that are similar to those presented here. Recent work has also shown that there are complex hybrid structure that combine standard building blocks with other structural elements. An example of this is seen for the homologous series $A_{n+1}M_nX_{3n+1}$ (A = lanthanide, M = transition metal, X = tetrels, and n = 1–6), which are constructed from basic structural subunits such as AlB_2 , $AuCu_3$, and $BaNiSn_3$ (Fig. 1f). Examples spanning n = 1 - 6 for the A = Ce series have already been uncovered, [23–25] where complex magnetism and Kondo lattice physics is observed. For example, $Ce_7Co_{6+x}Ge_{19-y}Sn_y$ (n = 6), with four crystallographically unique lanthanide sites, was recently shown to have five magnetic transitions of 5, 6, 7.2, 12.4, and 16.5 K. It was also shown that three of the n = 6 magnetic transitions are also found in the n = 5 member. [24] This opens the possibility that magnetic/electronic behaviors can be controlled using varied stacking arrangements. The diversity of this behavior invites further investigations, where we expect (i) additional n variation and (ii) chemical flexibility on all of the crystallographic sites. Indeed, it is easy to look forward to (i) the Eu, Yb, and U analogues being hosts for many different novel electronic/magnetic behaviors and (ii) the transition metal and tetrel sites accomodating isoelectronic replacement, and possibly even nonisoelectronic substitution. While a brute force examination of the chemical phase space is not feasible, our maps offer a route forward. For example, all of the Ce-based examples that have been uncovered so far exhibit local f-moment magnetism. Taking inspiration from the maps for the $ThCr_2Si_2$ Ce-based materials, this implies that efforts should be made to increase the hybridization strength by compressing the unit cell

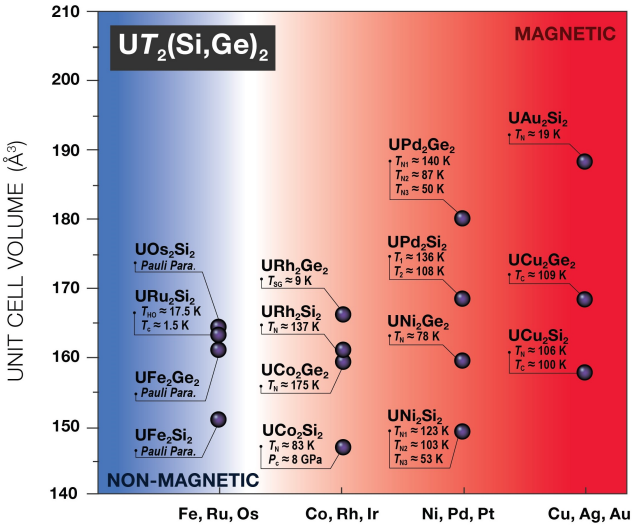

FIG. 6. **Phase map for the valence and ground state behavior of the compounds UT_2X_2 (T = transition metal and X = Si/Ge) that crystallize in the $ThCr_2Si_2$-type structure [1, 79, 132–146].** The white band separates the examples with Pauli paramagnetism (left hand side (blue background)) from those with magnetically ordered ground states (right hand side (red background)) is a guide to the eye. Ordering temperatures are labeled (Neel temperature T_N, Curie temperature T_C, hidden order temperature T_{HO}, spin glass temperature T_{sg}, and superconducting transition temperature T_c). Critical pressures P_c are labeled. These values and their associated references are summarized in Table S4.

volume (e.g., using applied pressure or Ge → Si substitution) and undertaking chemical substitution studies that point towards the iron column.

V. SUMMARY AND CONCLUSION

In this review, we have constructed structural/chemical maps for intermetallics with the $ThCr_2Si_2$ structure, which reveal distinct regions where classes of f-state behaviors emerge. In particular, amongst the Ce, Eu, Yb, and U families, the cases with magnetic f-states are separated from those with strongly hybridized nonmagnetic f-states by a well contained crossover region that depends both on unit cell volume and electron shell filling. Importantly, the examples that exhibit emergent behavior that is associated with quantum criticality are found in the crossover region. This agrees with earlier perspectives (e.g., Doniach and Hill), but clarifies the role of chemical composition without resorting to computational methods. These insights will be useful to pinpoint regions of interest in families of materials related to the $ThCr_2Si_2$ prototype and have the potential to accelerate discoveries of novel phenomena. This approach may even be applicable to other structural families, where mining of electronic databases could be used to accelerate progress.

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