Intermediate valence state in YbB$_4$ revealed by resonant x-ray emission spectroscopy

Felix Frontini$^{1,*}$, Blair W Lebert$^1$, K K Cho$^2$, M S Song$^2$, B K Cho$^2$, Christopher J Pollock$^3$ and Young-June Kim$^{1,*}$

$^1$ Department of Physics, University of Toronto, 60 St. George Street, Toronto, ON M5S 1A7, Canada
$^2$ School of Materials Science and Engineering, Gwangju Institute of Science and Technology, 61005 Gwangju, Republic of Korea
$^3$ Cornell High Energy Synchrotron Source (CHESS), Cornell University, Ithaca, NY 14853, United States of America

E-mail: felix.frontini@mail.utoronto.ca and youngjune.kim@utoronto.ca

Abstract
We report the temperature dependence of the Yb valence in the geometrically frustrated compound YbB$_4$ from 12 to 300 K using resonant x-ray emission spectroscopy at the Yb L$_{\alpha}$ transition. We find that the Yb valence, $v$, is hybridized between the $v=2$ and $v=3$ valence states, increasing from $v=2.61 \pm 0.01$ at 12 K to $v=2.67 \pm 0.01$ at 300 K, confirming that YbB$_4$ is a Kondo system in the intermediate valence regime. This result indicates that the Kondo interaction in YbB$_4$ is substantial, and is likely to be the reason why YbB$_4$ does not order magnetically at low temperature, rather than this being an effect of geometric frustration. Furthermore, the zero-point valence of the system is extracted from our data and compared with other Kondo lattice systems. The zero-point valence seems to be weakly dependent on the Kondo temperature scale, but not on the valence change temperature scale $T_v$.

Keywords: Kondo physics, intermediate valence, frustrated magnetism, x-ray spectroscopy

1. Introduction

In geometrically frustrated systems, frustration arises from the inability to minimize the total energy of competing antiferromagnetic interactions, resulting in a plethora of possible novel magnetic ground states [1]. Perhaps the most well known example of this is the theoretical spin $1/2$ Kagomé lattice whose ground state is truly disordered and continues to fluctuate in the absence of thermal energy, a so-called quantum spin liquid [2]. Another interesting real-world example of magnetic frustration is found in the family of rare-earth (RE) tetraborides REB$_4$ (RE = La, Ce, ... , Yb, Lu). The REB$_4$ family crystallizes in a tetragonal structure (space group $P4/nmm$), shown in figure 1(a) that can be mapped to the frustrated Shastry–Sutherland lattice within the $ab$ plane [3]. Frustration in the Shastry–Sutherland lattice is quantified by the relative strengths of the nearest and next-nearest neighbour exchange interactions $J$ and $J'$ [4]. For $J'/J \gtrsim 1$, the formation of simple Néel-type antiferromagnetic order is suppressed and novel magnetic properties are observed, such as the fractional magnetization plateaus observed in NdB$_4$ and HoB$_4$ [5]. When frustration is tuned higher ($J'/J \gtrsim 2$), long range magnetic order is entirely suppressed by the formation of a valence

* Authors to whom any correspondence should be addressed.

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interaction, characterized by a system specific hybridization when it is large the result is an intermediate valence (IV) system, characterized by charge fluctuations and a strong physical hybridization of valence states \[10, 11\]. That is to say, an IV Yb-based system possesses an electron configuration that is quantum mechanically mixed between \(|\{\text{Xe}\}f^{13}\text{6s}^2\text{5d}^1\rangle\) (Yb\(^{1+}\)) and \(|\{\text{Xe}\}f^{14}\text{6s}^2\rangle\) (Yb\(^{2+}\)) configurations: \(|\psi\rangle = \alpha|\{\text{Xe}\}f^{13}\text{6s}^2\text{5d}^1\rangle + \beta|\{\text{Xe}\}f^{14}\text{6s}^2\rangle\). Practically, the degree of hybridization is quantified by the average number of holes \(n_h\) in the 4\(f\) band, which deviates from \(n_h = 1\) as hybridization strength increases. This is related to overall valence simply by \(v = 2 + n_h\), where \(v\) is the Yb valence.

YbB\(_4\) was first hypothesized to possess ‘abnormal valency’ in 1972 based on abnormality of its lattice parameters, but has only recently been formally proposed as an IV metal based on profiles of the resistivity, in-plane magnetic susceptibility, and pressure dependence of the magnetic susceptibility \[12–14\]. However, still to date no direct confirmation of IV through spectroscopic method has been carried out. In this paper, we seek to address this knowledge gap by directly characterizing the valence state in YbB\(_4\) using x-ray spectroscopy. X-ray absorption spectroscopy (XAS) has proven to be an invaluable tool in studying valence hybridization in RE systems due to its relative experimental simplicity, and its nature as a truly bulk sensitive probe. In particular, this differentiates XAS from other techniques such as photo-emission spectroscopy which may only probe surface or near surface properties \[15, 16\]. The primary limitation of XAS, however, is the precision with which absorption features can be resolved. With experiments performed at the RE \(L_3\) edge (2p\(^{3/2}\) \(\rightarrow\) 5d), a standard in valence spectroscopy, the ability to resolve white line features is hampered by the large spectral width, a by-product of the short lifetime of the final state 2\(p\) core hole. The development of resonant x-ray emission spectroscopy (RXES) has significantly improved the resolution of such experiments, due to the significantly longer lifetime of the fluorescence final state core hole. In particular, high energy resolution fluorescence detected x-ray absorption spectroscopy (HERFD-XAS) measures x-ray absorption by monitoring the intensity of the fluorescence line. For an \(L_3\) edge experiment, the \(L_{31}\) decay channel (3d\(^{3/2}\) \(\rightarrow\) 2p\(^{3/2}\)) is typically monitored, putting the spectral width dependency on the lifetime of a 3\(d\) core-hole, which decreases the spectral width from ~4.3 eV to ~1.4 eV \[17, 18\].

We have used RXES techniques to directly confirm that YbB\(_4\) exists in an IV state at all measured temperatures, with a non-integer valence that increases from \(v = 2.61 \pm 0.01\) at 12 K to \(v = 2.67 \pm 0.01\) at 300 K. We compare the temperature scaling of the 4\(f\) hole occupancy in YbB\(_4\) to other Yb-based Kondo systems and find that the universal scaling observed in weakly mixed-valent Kondo lattices does not extend to systems, YbB\(_4\) included, in the IV regime \[19\]. We instead find that there appears to be no constraints based on zero point valence of the temperature scale of valence change in IV systems. We also investigate the extension of the power
law relationship observed between the zero point valence and Kondo temperature $T_K$ in weakly mixed-valent Kondo lattices and systems in the IV regime. A power law is found to be appropriate, however, in contrast to the previous scaling exponent of $n = 2/3$, an exponent of $n \sim 1/3$ is found to be more appropriate for a wider range of materials including IV compounds [19].

2. Experimental details

X-ray spectroscopy measurements were performed at the Cornell High Energy Synchrotron Source (CHESS) at the PIPOX beamline. To prepare the sample, a YbB$_4$ single crystal was ground and diluted with BN powder to two absorption lengths just above the Yb $L_3$ edge. The experiment was performed at the Yb $L_3$ edge ($E_i = 8.9436$ keV) while monitoring fluorescence in the $L_{\alpha\alpha}$ decay channel ($E_f \sim 7.415$ keV). On the incident optics side, a cryogenically cooled Si(311) double crystal monochromator was used. Rhodium coated vertical and horizontal focusing mirrors set to 4 mrad were employed for the purposes of harmonic rejection. The beam was focused to a spot size of $100 \times 400 \mu m^2$ at the sample, with a flux of $\sim 3.1 \times 10^{11}$ ph s$^{-1}$ at 8.980 keV. For the receiving optics, a Johann-type spectrometer equipped with spherically-bent Si(620) crystal analyzers (radius 0.85 m) and a Pilatus 100 K solid-state detector were used. We scanned the incident x-ray energy range 8.935–8.970 keV at constant emitted x-ray energy and iterated while incrementing the selected emitted x-ray energy, scanning the emitted x-ray energy range of 7.3995–7.4301 keV to create a 2D RXES map of emission intensity. Transmission through a Yb reference foil was monitored in order to calibrate the incident energy. This was done by fitting the Yb reference absorption to determine the energy shift needed such that the absorption inflection point coincides with the Yb $L_3$ edge ($E_i = 8.9436$ keV [30]). Temperature dependence was studied from the base temperature of 12 K up to 300 K using a closed cycle refrigerator. During the experiment, the beam spot was rastered every five incident energy scans (∼20 min) to avoid beam damage. No sample degradation was observed in this time frame during initial testing. Due to manual packing of the powder, it was necessary to correct the data taken at different sample positions for concentration variations. Normalization factors to account for variations in concentration were obtained by tuning the incident x-ray energy to well above the $L_3$ absorption edge and measuring the intensity of fluorescence at each of the raster positions.

3. Results

3.1. HERFD-XAS

In figure 2(a) we show the RXES scans at 12 K in a 2D pseudocolour map. The map is plotted against axes of incident x-ray energy $E_i$ along the vertical and transferred energy $E_t$ along the horizontal, where $E_t = E_i - E_f$ is simply the difference between incident and emitted x-ray energies. In this plot the diagonal corresponds to cuts with constant emitted x-ray energy $E_f$. The highlighted diagonal corresponds to the monitored x-ray fluorescence at the nominal $L_{\alpha\alpha}$ transition (x-rays of constant emitted energy $E_f \sim 7.4145$ keV) measured as incident energy is scanned. This is the nominal HERFD-XAS spectrum, which is shown in greater detail in figure 2(c). The HERFD-XAS spectrum is particularly useful since it provides the true relative population of the Yb$^{2+}$ and Yb$^{3+}$ states, given by the ratio of the integrated intensities of the respective components, while providing a large advantage in energy resolution compared to standard XAS. The HERFD-XAS spectrum was curve fitted to extract the intensity of the Yb$^{2+}$ and Yb$^{3+}$ components. Figure 2(c) shows the individual contributions of the Yb$^{2+}$ and Yb$^{3+}$ lineshapes, the latter of which lies higher in energy due to the additional repulsive coulomb interaction between the intermediate state $2p_{3/2}$ core hole and the Yb$^{3+}$ $4f$ hole that is not present in the Yb$^{2+}$ state. The Yb$^{2+}$ lineshape consists of a peak to fit the $L_3$ edge white line and an arctangent step function to fit the background above-edge absorption to continuum. We find that quality of fit necessitates the use of a doublet peak, which we fit with two Gaussian functions separated in energy by ∼3.7 eV, with the first peak centred at 8.948 keV. This splitting is a common feature in the absorption spectra of Yb based IV materials and is attributed to crystal field splitting of the $5d$ levels, an explanation we believe to be applicable in our case as there is evidence of large crystal field effects in YbB$_4$ [13, 31, 32]. The Yb$^{3+}$ component is fitted with the same lineshape shifted in energy by ∼6 eV, with the addition of a peak in the pre-edge region. This pre-edge peak has previously been attributed to the dipole forbidden quadrupolar $2p_{3/2} \rightarrow 4f$ transition from the core hole to the Yb$^{3+}$ $4f$ vacancy [33]. The intensity of the Yb$^{2+}$ feature is given by the integrated intensity of the doublet peak, while the intensity of the Yb$^{3+}$ feature is given by the integrated intensity of the doublet and pre-edge peaks. In both cases the intensity due to the background step function is not considered. We also observe a feature at high energy which is fitted with a Gaussian function peaked at 8.962 keV. This is attributed to normal fluorescence and is fitted solely for aesthetic purposes; its removal does not affect our results.

Immediately evident from our fit of the HERFD-XAS spectra at 12 K is the existence of an intermediate, or non-integer, valence state in YbB$_4$, so evident by the fact that we fit non-zero intensities for the lineshapes corresponding to both Yb$^{2+}$ and Yb$^{3+}$ valence states. This suggests that the lack of magnetic order in YbB$_4$ is attributable to the dominance of the Kondo effect. We extend this fitting procedure to the HERFD-XAS spectra at all measured temperatures to quantify any temperature dependence. In figure 3(a) we show fitted HERFD-XAS spectra measured between 12 and 300 K. We visually observe that the Yb$^{2+}$ feature is suppressed as temperature increases while the Yb$^{3+}$ is enhanced. This is less obvious with the pre-edge Yb$^{3+}$ peak due to the reduced scale of the feature and bleed from the tail of the Yb$^{2+}$ peak which scales oppositely. To quantify these changes we examine the temperature dependence of the Yb$^{2+}$ feature intensity compared to its measured intensity at 12 K, illustrated in figure 3(c). We find that the Yb$^{2+}$ feature intensity decreases...
Figure 2. (a) YbB$_4$ L$_\alpha_1$ RXES colourmap measured at 12 K with HERFD-XAS cut at L$_\alpha_1$ nominal and RXES cut at Yb$^{2+}$ resonance illustrated. (b) RXES cuts as $E_i$ is tuned from 8.935 to 8.97 keV, with HERFD-XAS cut illustrated and Yb$^{2+}$ resonance highlighted. (c) HERFD-XAS cut and corresponding fit at 12 K. (d) RXES cut at Yb$^{2+}$ resonance and corresponding fit at 12 K.

3.2. RXES

By monitoring x-ray fluorescence while scanning emitted x-ray energy and with incident energy tuned to Yb$^{2+}$ resonance we obtain the desired RXES spectrum, illustrated in figure 2(d) for the measurement at 12 K. Yb$^{2+}$ resonance is here defined as the incident energy point closest to the Yb$^{2+}$ peak energy from our HERFD-XAS fit ($E_i = 8.948$ keV). From our total 2D RXES map, this is taken as a single incident energy cut, as illustrated in figure 2(a). Though the RXES spectrum does not provide the direct equivalency between intensity and fractional population that HERFD-XAS does, it provides us with the ability to selectively enhance the intensity of the weaker Yb$^{2+}$ component, as illustrated in figure 2(b). This enhancement in intensity aids in more accurately tracking the temperature scaling of the Yb$^{2+}$ component intensity and is often critical for systems with smaller Yb$^{2+}$ contributions [19]. In the case of YbB$_4$, however, the Yb$^{2+}$ component is strong enough to be well resolved in the HERFD-XAS spectrum. Instead, RXES is used to validate the HERFD-XAS results and provide a quantitative metric for estimating the uncertainty in our valence estimates.

In order to accurately determine the change in the Yb$^{2+}$ component intensity with temperature it is necessary to possess a consistent total emission intensity scale at all temperatures. We found that the scaling performed to correct for variations in concentration was insufficient for this purpose and that a second normalization was required. To this end, we normalize by the summed integrated intensities of the Yb$^{2+}$ and Yb$^{3+}$ HERFD-XAS features, such that the total integrated intensity of the HERFD-XAS is scaled to unity at every temperature. This also simplifies further analysis in that the integrated intensity of each HERFD-XAS feature is now directly equal to the fractional occupation of the corresponding electronic state. Following this normalization the RXES spectrum was fitted to extract the individual Yb$^{2+}$ and Yb$^{3+}$ lineshapes. Figure 2(d) shows the individual contributions from the Yb$^{2+}$ and Yb$^{3+}$ lineshapes, the latter of which lies higher in energy due to the additional repulsive coulomb interaction between the final state 3$d^{5/2}$ core hole and the Yb$^{3+}$ 4$f$ hole. The Yb$^{2+}$ lineshape is comprised of a single pseudo-Voigt function peaked at 1.532 keV. The Yb$^{3+}$ lineshape is composed of a pseudo-Voigt function peaked at 1.538 keV with an asymmetric pseudo-Voigt function to fit the extended fluorescence tail. As with our fit of the HERFD-XAS spectrum, our fit of the RXES spectrum indicates an IV state in YbB$_4$. We extend this fitting procedure to all temperatures and investigate the temperature dependence of the RXES spectrum, as shown in figure 3(b). We observe that, as in the HERFD-XAS spectrum, the Yb$^{2+}$ feature is suppressed as temperature increases from 12 to 300 K. A slight enhancement of the Yb$^{3+}$ feature is also observed with increasing temperature, however this change...
is not large due to the fact that we are off-resonance of the Yb$^{3+}$ feature. These changes are quantified in the same way as the HERFD-XAS spectrum, by examining the temperature evolution of the Yb$^{2+}$ feature, shown alongside the HERFD-XAS estimate in figure 3(c). Using RXES we observe the same reduction of $\sim 15\%$ in the Yb$^{3+}$ feature intensity between 12 and 300 K. While the relative change in Yb$^{2+}$ intensity is interesting, we are more interested in the absolute change and overall scale of the Yb valence in YbB$_4$. We calculate this by proxy of the deviation in the 4$f$ hole occupancy from $n_h = 1$, which we note as $\Delta n_h = 1 - n_h$, and which is related to the valence by $v = 3 - \Delta n_h$. Physically, $\Delta n_h$ represents the fractional occupation of the Yb$^{2+}$ state. We determined $\Delta n_h$ using the intensity of the Yb$^{2+}$ and Yb$^{3+}$ features at each temperature, shown in figure 4. Alongside several other Yb-based Kondo lattice systems for comparison. In the HERFD-XAS spectra, $\Delta n_h(T)$ is simply equal to the normalized integrated intensity of the Yb$^{2+}$ peak at temperature $T$, $I_{2+}(T)$. For the RXES spectra, because of its resonant nature, we adopt a starting value from HERFD-XAS. We adopt the value at 12 K where the Yb$^{2+}$ component is largest, and hence where the HERFD-XAS fit is the most reliable. From this point, the RXES estimation displayed lack of magnetic order. Our results also show that the intensity of the Yb$^{2+}$ component in both HERFD-XAS and RXES spectra is temperature dependent, with it decreasing in intensity by $\sim 15\%$ between 12 and 300 K. While the relative change in Yb$^{2+}$ intensity is interesting, we are more interested in the absolute change and overall scale of the Yb valence in YbB$_4$. 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4. Discussion

Our experimental results confirm that YbB$_4$ is in an IV state at all temperatures, a clear indication that the Kondo interaction in YbB$_4$ is strong and is therefore likely responsible for the
of $\Delta n_\text{h}(T)$ is given by this value scaled by the change in the RXES spectrum Yb$^{2+}$ intensity relative to its value at 12 K

$$\Delta n_\text{h}(T) = I_{2+}(T) \cdot \frac{\Delta n_\text{h}(12 \text{ K})}{I_{2+}(12 \text{ K})}.$$ 

Our calculations reveal that $\Delta n_\text{h}(T)$ decreases monotonically from 0.39 ± 0.01 at 12 K to 0.33 ± 0.01 at 300 K. This translates to a change in valence from $v = 2.61 ± 0.01$ to $v = 2.67 ± 0.01$.

To understand the temperature dependence of Yb valence, we employ the method of Kummer et al to estimate the zero point Yb$^{2+}$ occupancy, $\Delta n_\text{h}(0)$, and the characteristic valence change temperature $T_\text{v}$ [19, 45]. Here $T_\text{v}$ simply corresponds to the temperature at which $\Delta n_\text{h}(T) = 1/2 \Delta n_\text{h}(0)$. These are estimated by an empirical model which takes the form

$$\Delta n_\text{h}(T) = \Delta n_\text{h}(0)/[1 + (2^{1/0.21} - 1)(T/T_v)^{2/0.21}]^{0.21} \tag{1}$$

The empirical form of equation (1) fits our data well, and returns a zero point Yb$^{2+}$ occupancy of $\Delta n_\text{h}(0) = 0.390 ± 0.003$, as well as a valence change temperature $T_v$ on the order of 1500 K. Comparison to other Yb-based Kondo systems shows qualitatively similar temperature scaling of the Yb$^{2+}$ occupancy amongst all the compounds, however, the normalized scaling in figure 4(b) illustrates some notable differences. In particular, it appears that the scaling of the Yb$^{2+}$ occupancy is slower for systems that are more strongly mixed-valent (i.e. have larger $\Delta n_\text{h}(0)$).

To quantify this, we have compared the fitted values of $T_v$ and $\Delta n_\text{h}(0)$ of various Yb-based Kondo systems, illustrated in figure 5(a). In figure 5(b) we plot $\Delta n_\text{h}(0)$ vs. the reported Kondo temperatures $T_K$ available from literature of the selected compounds. Note that all values of $T_v$ and $\Delta n_\text{h}(0)$ are obtained using equation (1) to provide consistency, and that while other choices of model give different values for $T_v$, the hierarchy of scaling between compounds is quite robust. As such, we put little stock in the absolute values of $T_v$ and rather focus on the differences between compounds. To this point, we note that the plotted errorbars reflect the model uncertainty and are therefore most useful in interpreting differences between compounds but do, however, depend on the model chosen and therefore do not fully reflect the estimate accuracy. As illustrated in figure 5, though there appears to be a rough scaling relationship between $\Delta n_\text{h}(0)$ and $T_K$, there does not appear to be such a relationship between $\Delta n_\text{h}(0)$ and $T_v$. We note that the scaling relationship is likely rough in part due to differences in $T_v$ was estimated across the selected literature. The scaling relationship between $\Delta n_\text{h}(0)$ and $T_K$ is fitted to a power law of the form $\Delta n_\text{h}(0) \propto aT_K^n$, with $a \sim 1/30$ and $n \sim 1/3$. This exponent is quite different from the exponent of $n \sim 2/3$ found by Kummer et al illustrated in figure 5(b) for reference, a difference we attribute to choice of reference materials used for comparison, in particular the fact that we choose to focus on IV compounds (here phenomenologically defined as $\Delta n_\text{h}(0) \gtrsim 0.15$) whereas such materials are excluded from the analysis of Kummer et al [19]. Agreed upon by both our analysis and that of Kummer et al is the existence of a sub-linear scaling relationship between $\Delta n_\text{h}(0)$ and $T_K$. As noted by Kummer et al it is expected that the precise nature of this relationship is complex, but is in agreement with a sub-linear relationship.

In figure 5(a), we illustrate that for materials that are only moderately mixed-valent ($\Delta n_\text{h}(0) \lesssim 0.15$), it appears that the valence change temperature $T_v$ is more or less fixed, on the order of ~300 K, as was shown by Kummer et al [19]. On the other hand, for materials in the IV regime this breaks down and instead it appears as if there are no constraints on $T_v$, with values ranging over more than an order of magnitude. This suggests that $T_v$ for IV systems is neither universal nor proportional to the strength of the Kondo interaction, and may instead be influenced in a more complex manner by external variables. This view is reinforced by a deeper comparison of YbB$_4$ and its closest analog in terms of both $T_v$ and $\Delta n_\text{h}(0)$, $\alpha$-YbAlB$_4$.

Both $\alpha$-YbAlB$_4$ and YbB$_4$ possess an enhanced mass Fermi-liquid ground state and both systems have similar

![Figure 5](image-url)
magnetic susceptibility profiles, with strong Ising anisotropy along the c-axis [13, 28, 46]. The crystal structure of both systems are shown in figure 1(b) for comparison. α-YbAlB₄ possesses an orthorhombic crystal structure (space group Pbam), with layers of Yb–Al and B atoms stacked alternately along the crystal c-axis, and is visually similar to YbB₄. In the Yb atom local environment of both materials there are striking similarities. In both materials, the B atoms are arranged in two overlapping heptagonal rings above and below the Yb atom along the c-axis. Furthermore, the in-plane Yb–Yb nearest and next-nearest neighbour separations are 3.740 and 3.777 Å in α-YbAlB₄ compared to 3.681 and 3.720 Å in YbB₄ [23, 29]. Electronic density of states calculations shown in figures 1(c) and (d) also show similarities between α-YbAlB₄ and YbB₄. By DOS calculations both are metallic. Both show stronger contributions from B atom electrons below the Fermi level, indicative that the Kondo interaction in YbB₄ is likely the mechanism preventing the formation of magnetic order in YbB₄, suggesting that long range order is suppressed by the dominance of the Kondo interaction rather than by the effects of geometric frustration. We also estimate the zero point Yb²⁺ occupancy Δn₀(0) and temperature scale of valence change Tᵥ in YbB₄, finding Δn₀(0) ~ 0.39 and Tᵥ ~ 1500 K. We compared this temperature scale with that of other Yb-based Kondo lattices. We observe that Δn₀(0) and the reported Kondo temperatures T_K seem to be weakly correlated with a power law relationship with an exponent of n ~ 1/3. On the other hand, we find no correlation between Tᵥ and Δn₀(0) for systems in the IV regime, indicating that Tᵥ depends significantly on variables other than the Kondo interaction strength. Anecdotal evidence based on similarities between YbB₄ and α-YbAlB₄ suggests that local environment, crystal anisotropy, and electronic structure may be among the external variables affecting Tᵥ.

5. Conclusion

We have studied the Yb valence in YbB₄ as a function of temperature between 12 and 300 K using HERFD-XAS and RXES at the Yb L₃ transition. We find that the Yb valence is physically hybridized between the Yb²⁺ and Yb⁺⁺ valence states, increasing monotonically from v = 2.61 ± 0.01 at 12 K to v = 2.67 ± 0.01 at 300 K. We are thus able to confirm that YbB₄ is a Kondo system with hybridization strength sufficient to place the system in the IV regime at all temperatures. This is indicative that the Kondo interaction in YbB₄ is significant and therefore is likely the mechanism preventing the formation of magnetic order in YbB₄, suggesting that long range order is suppressed by the dominance of the Kondo interaction rather than by the effects of geometric frustration. We also estimate the zero point Yb²⁺ occupancy Δn₀(0) and temperature scale of valence change Tᵥ in YbB₄, finding Δn₀(0) ~ 0.39 and Tᵥ ~ 1500 K. We compared this temperature scale with that of other Yb-based Kondo lattices. We observe that Δn₀(0) and the reported Kondo temperatures T_K seem to be weakly correlated with a power law relationship with an exponent of n ~ 1/3. On the other hand, we find no correlation between Tᵥ and Δn₀(0) for systems in the IV regime, indicating that Tᵥ depends significantly on variables other than the Kondo interaction strength. Anecdotal evidence based on similarities between YbB₄ and α-YbAlB₄ suggests that local environment, crystal anisotropy, and electronic structure may be among the external variables affecting Tᵥ.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD

Felix Frontini  https://orcid.org/0000-0002-4179-3428

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