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## 4f-Orbital mixing increases the magnetic susceptibility of Cp'<sub>3</sub>Eu<sup>†</sup>

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Traditional models of lanthanide electronic structure suggest that bonding is predominantly ionic, and that covalent orbital mixing is not an important factor in determining magnetic properties. Here, 4f orbital mixing and its impact on the magnetic susceptibility of Cp'<sub>3</sub>Eu (Cp' = C<sub>5</sub>H<sub>4</sub>SiMe<sub>3</sub>) was analyzed experimentally using magnetometry and X-ray absorption spectroscopy (XAS) methods at the C K-, Eu M<sub>5,4</sub>-, and L<sub>3</sub>-edges. Pre-edge features in the experimental and TDDFT-calculated C K-edge XAS spectra provided unequivocal evidence of C 2p and Eu 4f orbital mixing in the π-antibonding orbital of a' symmetry. The charge-transfer configurations resulting from 4f orbital mixing were identified spectroscopically by using Eu M<sub>5,4</sub>-edge and L<sub>3</sub>-edge XAS. Modeling of variable-temperature magnetic susceptibility data showed excellent agreement with the XAS results and indicated that increased magnetic susceptibility of Cp'<sub>3</sub>Eu is due to removal of the degeneracy of the <sup>7</sup>F<sub>1</sub> excited state due to mixing between the ligand and Eu 4f orbitals.

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## Introduction

The ability to harness the 4f-orbital anisotropies and magnetic susceptibilities of lanthanide (Ln) elements is key to their application in molecular magnetism, including as molecular qubits and single-molecule magnets (SMMs). For example, in the field of SMMs, chemists have developed ligand design principles<sup>1–7</sup> that facilitate subtle tuning of the crystal field, which in turn enhances magnetic anisotropy and the blocking temperature in single-ion<sup>8–15</sup> magnets. In addition to the 4f crystal field, lanthanide magnetic properties can be influenced by strong electron correlations, generating effects such as homogenous mixed valence with magnetic singlet formation and valence tautomerism.<sup>16–22</sup> However, the impact of covalent

mixing between metal and ligand orbitals on the magnetic properties of trivalent lanthanide systems is typically small, compared to its more significant effect in actinide complexes<sup>23–29</sup> and in certain tetravalent lanthanide complexes.<sup>30–36</sup> The Ln 4f orbitals have limited radial extension, such that the effect of overlap between the 4f and ligand orbitals is much weaker than electron repulsion and spin-orbit coupling.<sup>37</sup> Covalent interactions between ligands and contracted 4f orbitals have been identified by recent theoretical and spectroscopic studies of Ln(III) compounds.<sup>19–21,38–42</sup> Despite this progress, it remains challenging to predict how charge transfer resulting from 4f orbital mixing will be manifested by changes in magnetic behaviour.<sup>43</sup>

Denning and coworkers previously quantified 4f shell covalency in Cp<sub>3</sub>Yb in terms of charge-transfer from the ligand to the metal center using X-ray photoelectron spectroscopy (XPS), EPR (HYSCORE), and optical spectroscopies.<sup>39,40</sup> They hypothesized<sup>40</sup> that 4f shell covalency could also be significant in Cp<sub>3</sub>Eu because, like Yb<sup>3+</sup>, Eu<sup>3+</sup> has a low-energy charge transfer state.<sup>44</sup> In fact, Cp'<sub>3</sub>Eu (Cp' = trimethylsilylcyclopentadienyl) has a more positive redox potential relative to Cp'<sub>3</sub>Yb (−1.07 V vs. −1.64 V, respectively),<sup>45</sup> and Eu and Yb have the most favourable third ionization potentials of the entire lanthanide series (24.92 ± 0.10 eV and 25.05 ± 0.03 eV, respectively).<sup>46</sup> Electron delocalization has been observed in Eu intermetallics; however, evidence of similar effects in molecules is limited.<sup>47</sup> 4f orbital mixing in an organometallic Eu(III) compound, Cp<sub>3</sub>Eu(THF), was illustrated by an unprecedentedly negative isomer shift in

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its 151-Eu Mössbauer spectrum.<sup>38</sup> Laboratory XPS has recently been applied to study the electronic structures of Cp<sub>3</sub>Ln and [K(crypt)][Cp<sub>3</sub>Ln] (Ln = Gd, Eu, Sm, Tb), but spectral signatures for charge transfer were not observed.<sup>48</sup> Direct probes of 4f orbital mixing are needed to understand the relationship between charge transfer and magnetism in lanthanide organometallic complexes.

Studies of lanthanide and actinide organometallic compounds have shown that C K-edge XAS provides unique insight into the interactions between π systems and metal orbitals in specific valence orbitals.<sup>49–51</sup> We previously used a combination of C K-edge XAS and DFT to provide direct evidence of C 2p and Ce 4f orbital mixing in the δ-antibonding orbitals of (C<sub>8</sub>H<sub>8</sub>)<sub>2</sub>Ce.<sup>50</sup> Here, we use C K-edge XAS and time dependent density functional theory (TDDFT) calculations to provide direct evidence of 4f orbital mixing in Cp<sub>3</sub>Eu. In addition, Eu L<sub>3</sub>- and M<sub>5,4</sub>-edge spectroscopies were used to show how the 4f-orbital mixing results in C 2p → Eu 4f charge transfer. Taken together with variable temperature magnetic susceptibility measurements, these spectroscopic evaluations reveal how 4f-orbital mixing can impact magnetism in lanthanide organometallic complexes.

## Results and discussion

### Ground state electronic structure

The following discussion of the molecular orbital interactions in Cp<sub>3</sub>Eu provides a framework for evaluating the experimental results. Because the electronic structures for Ln(C<sub>5</sub>R<sub>5</sub>)<sub>3</sub> (R=H or alkyl) are well established,<sup>40,52–55</sup> this discussion will focus on the metal-based orbitals that are relevant to the XAS experiments. Visual depictions comparing the effects of spin-orbit coupling, ligand field splitting, and coulombic repulsion have been published for f<sup>1</sup> systems,<sup>7,56</sup> but are not possible for Eu<sup>3+</sup> due to the large number of states involved. Hence, an MO model for the interaction between 2p-π orbitals on the [Cp<sub>3</sub>]<sup>3-</sup> fragment and the Eu 5d- and 4f-orbitals was constructed in

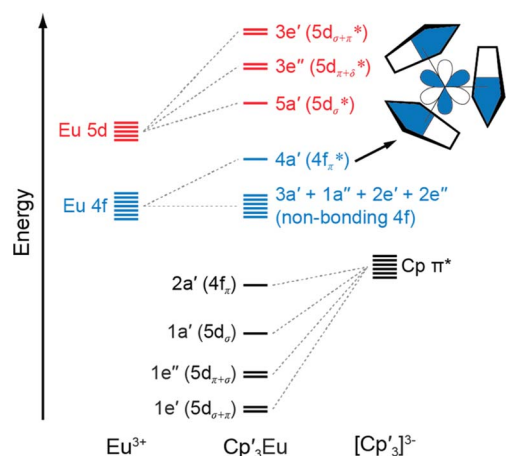


Fig. 1 A qualitative MO diagram of Cp<sub>3</sub>Eu in C<sub>3h</sub> symmetry. The inset shows the a' antibonding interaction of metal f and ligand orbitals. The nodal characteristics of the (Cp)<sub>3</sub><sup>3-</sup> fragment relative to the metal atom are represented with common short-hand notation.<sup>53,57</sup>

pseudo-C<sub>3h</sub> symmetry (Fig. 1).<sup>40</sup> In C<sub>3h</sub>, the 5d orbitals on Cp<sub>3</sub>Eu transform as a' (d<sub>z<sup>2</sup></sub>), e' (d<sub>xy</sub> and d<sub>x<sup>2</sup>-y<sup>2</sup></sub>), and e'' (d<sub>xz</sub> and d<sub>yz</sub>), which form σ-, π-, and δ-bonding interactions with the equatorial Cp' ligands. The Eu 4f orbitals transform as 2a' + a'' + e' + e'', most of which are best described as non-bonding. However, mixing between appropriate ligand orbitals and one of the 4f orbitals of a' symmetry gives rise to a weakly π-antibonding MO.<sup>58</sup> Such mixing with the 4f orbitals can be described using an MO model by the linear combination of orbitals as:

$$\Psi^* = N\{\psi_{4f} - \lambda\psi_{Cp' \pi^*}\} \quad (1)$$

where *N* is a normalization constant, λ is the orbital mixing coefficient, and ψ<sub>4f</sub> and ψ<sub>Cp' π\*</sub> are parent Eu and ligand-based wavefunctions. The MO model is advantageous because it describes how partial electron delocalization can occur in Cp<sub>3</sub>Eu due to specific types of orbital interactions (e.g., σ, π, δ, φ), and is best-suited to interpret ligand-based spectroscopies such as C K-edge XAS (see below).

The MO model does not account for exchange interactions or core-hole induced charge transfer, among other effects associated with the multi-electron 4f<sup>6</sup> configuration of a Eu<sup>3+</sup> ion. Hence, the single-determinant MO wavefunction shown in eqn (1) can be rewritten using a many-electron, configuration interaction (CI) model,<sup>50,59</sup> where the ground state is expressed by a combination of two terms that differ only by one electron:

$$\Psi^* = N\{|4f^6\rangle + \lambda|4f^7\bar{L}\rangle\} \quad (2)$$

where |4f<sup>6</sup>⟩ is the ionic, Eu<sup>3+</sup> configuration and |4f<sup>7</sup> $\bar{L}$ ⟩ describes the result of a ligand-to-metal electron transfer leading to reduction to Eu<sup>2+</sup> and formation of a ligand hole ( $\bar{L}$ ). Because the electrons are assumed to be fully localized, the CI model is better suited to interpret the metal-based Eu M<sub>5,4</sub>- and L<sub>3</sub>-edge XAS and magnetic measurements described below.

### Carbon K-edge XAS

C K-edge XAS spectra were collected with a scanning X-ray transmission microscope (STXM) on micron-scale crystallites of Cp<sub>3</sub>Eu (Fig. S4†).<sup>58</sup> This approach minimizes the saturation and self-absorption effects that commonly occur when using weakly penetrating incident radiation at low photon energies, and has been applied in the study of metal-carbon bonding for both d- and f-block systems.<sup>49,50,60</sup> The background-subtracted and normalized C K-edge spectrum of Cp<sub>3</sub>Eu is shown in Fig. 2A together with a curve-fit model. For the pre-edge region of the spectrum above 284 eV, the spectrum was fit using three Gaussian functions (refer to the ESI† for full details). The C K-edge spectrum of Cp<sub>3</sub>Eu also exhibited a small peak at low energy, which required a fourth Gaussian function at 283.6 eV. The presence of a transition in this energy range is unusual, since transitions below 284 eV have not been observed previously for a variety of 1st, 2nd, or 3rd row d-block metallocenes.<sup>60–63</sup> Because an equivalent low-energy peak was also not resolved in the C K-edge spectrum of 4f<sup>7</sup> Cp<sub>3</sub>Gd (see Fig. S6†), we hypothesized that the peak at 283.6 eV was associated with transitions into MOs of 4f-parentage.



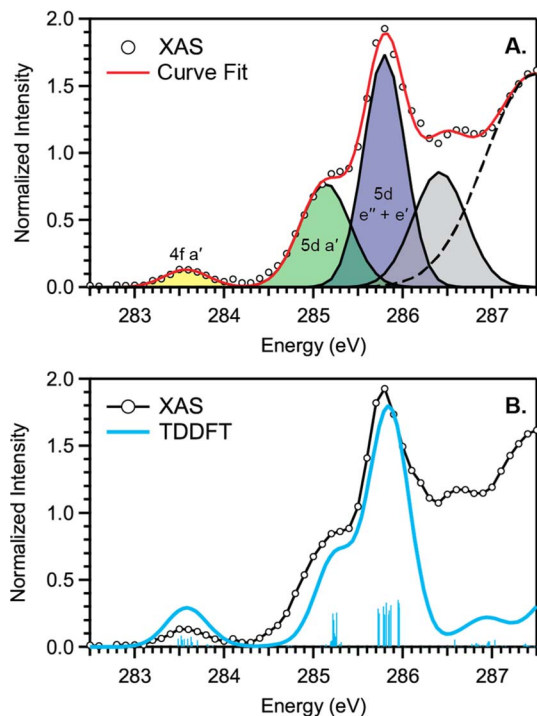


Fig. 2 (A) C K-edge XAS pre-edge of  $\text{Cp}'_3\text{Eu}$  (black circles), Gaussian functions (yellow, green, blue, and gray), and the sum of post-edge functions (dashed black trace) used to generate the total curve fit (red). (B) C K-edge XAS experimental data for  $\text{Cp}'_3\text{Eu}$  (black circles), the TDDFT-calculated spectrum (blue) and calculated transitions (vertical blue bars). The three main features are labeled with the acceptor MOs from the transition assignments.

To assign the pre-edge features in the C K-edge XAS of  $\text{Cp}'_3\text{Eu}$ , the spectrum was modelled using TDDFT implemented with NWChem and using the long-range corrected LC-PBE0 functional.<sup>63</sup> Fig. 2B shows that the experimental spectrum for  $\text{Cp}'_3\text{Eu}$  was well-reproduced with this computational method. Examination of the acceptor orbitals associated with a group of 15 transitions centered at 283.6 eV confirms that the low-energy feature is associated with transitions from the C 1s orbitals into the Eu–Cp'  $\pi$ -antibonding 4f-orbital of  $a'$  symmetry. Both the experimental and TDDFT calculated C K-edge spectrum agree regarding the relative location of the 4f and 5d orbitals; each show that the C 1s  $\rightarrow a'$  ( $4f-\pi$ ) transition is 1.6 eV lower in energy than the lowest energy transition into the 5d manifold, C 1s  $\rightarrow a'$  ( $5d-\sigma$ ). Moving to higher energy, the TDDFT calculations indicate that the next feature at 285.8 eV is associated with C 1s transitions into both the  $e''$  ( $5d_{\pi+\delta}^*$ ) and  $e'$  ( $5d_{\sigma+\pi}^*$ ) orbitals. These transitions are close in energy and not resolved individually in the experimental spectrum. The fourth feature observed at 286.4 eV was not well reproduced in the calculated spectrum; features in this energy range are likely associated with Rydberg-type orbitals that are not the unoccupied, antibonding counterpart to bonding orbitals that are occupied in the ground-state.<sup>60</sup>

The C K-edge pre-edge transitions described above have intensities that are weighted by the amount of C 2p character in the acceptor MO. Hence, the C K-edge XAS and TDDFT

calculations provide evidence that C 2p and Eu 4f orbital mixing occurs specifically in the Eu–Cp'  $\pi$ -antibonding orbitals of  $a'$  symmetry. This assignment is consistent with the MO diagram derived experimentally from magnetometry (see below), which showed that the  $a'$  MO is the most destabilized by the Cp' ligand field. In this regard,  $\text{Cp}'_3\text{Eu}$  is similar to  $\text{Cp}'_3\text{Yb}$ , which also exhibits significant orbital mixing in the partially occupied  $a'$  orbital as shown by XPS and ADF-DFT calculations.<sup>39,40</sup> The consequence of mixing in the  $a'$  MO is Cp'  $\rightarrow$  Eu charge transfer. In a configuration interaction (CI) model where the orbitals are localized, this mixing is manifested by a greater weight of the  $\text{Eu}^{2+}$  configuration,  $4f^7\bar{L}$ , where  $\bar{L}$  represents a hole on one of the Cp' ligands resulting from Cp'  $\pi \rightarrow 4f$  charge transfer.<sup>22</sup> Charge transfer is also reflected in the DFT calculation for  $\text{Cp}'_3\text{Eu}$  by the Lowdin spin population analysis, which provided a value of 6.32. This value exceeds the prediction of 6 for a  $\text{Eu}^{3+}$  ion and suggests that the weight of the  $\text{Eu}^{2+}$  CT configuration ( $4f^{14}\bar{L}$ ) in the ground state is 32%.

### Europium $L_{3-}$ and $M_{5,4}$ -edge XAS

Eu  $M_{5,4}$ -edge and  $L_{3-}$ -edge XAS were obtained to provide further evidence of Cp'  $\pi \rightarrow 4f$  charge transfer interactions in  $\text{Cp}'_3\text{Eu}$ . Previous work has shown that  $M_{5,4}$ -edge and  $L_{3-}$ -edge XAS are particularly useful techniques for probing 4f orbital mixing and charge transfer in tetravalent Ce, Pr, and Tb systems,<sup>59,64–66</sup> and in trivalent Sm, Eu, Tm, and Yb systems.<sup>67–69</sup> Both the Eu  $L_3$  ( $2p \rightarrow 5d$ ) and  $M_{5,4}$ -edge ( $3d \rightarrow 4f$ ) spectroscopies probe electric-dipole allowed transitions from Eu core orbitals to empty or partially occupied valence orbitals.

Fig. 3 shows the background subtracted and normalized Eu  $M_{5,4}$ -edge XAS spectra for  $\text{Cp}'_3\text{Eu}$  compared to reference compounds for  $\text{Eu}^{2+}$  ( $\text{Eu}_2\text{O}_3$ ) and  $\text{Eu}^{3+}$  ( $\text{EuAl}_4$ ).<sup>69</sup> The spectra are split into low-energy  $M_5$  ( $3d_{5/2} \rightarrow 4f_{7/2}$ ) and high-energy  $M_4$  ( $3d_{3/2} \rightarrow 4f_{5/2}$ ) edges due to spin-orbit coupling with the 3d core

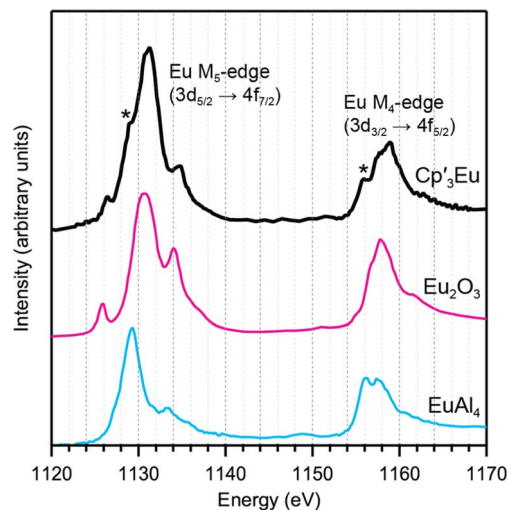


Fig. 3  $M_{5,4}$ -edge spectrum for  $\text{Cp}'_3\text{Eu}$  (black) and references for  $\text{Eu}^{3+}$  ( $\text{Eu}_2\text{O}_3$ , magenta) and  $\text{Eu}^{2+}$  ( $\text{EuAl}_4$ , blue). Two features associated with  $\text{Eu}^{2+}$  character in the  $L_{3-}$ -edge spectrum for  $\text{Cp}'_3\text{Eu}$  are highlighted with asterisks.



hole.<sup>70,71</sup> Both the  $M_5$ - and  $M_4$ -edges can also exhibit fine structure due to final-state multiplet splitting, with characteristic patterns based on the number of 4f electrons.<sup>50,59,72,73</sup> The spectrum of  $Cp'_3Eu$  consists of main  $M_5$  and  $M_4$  peaks centered at 1131.3 eV and 1158.9 eV, respectively, and fine structure that most clearly resembles the spectrum of  $Eu_2O_3$ .<sup>70,71,74</sup> However, additional features were also observed at 1129.1 and 1155.9 eV, which were not present in the spectrum for  $Eu_2O_3$  but were coincident with the peak energies of the  $Eu^{2+}$  standard,  $EuAl_4$ .<sup>69</sup> In this regard the  $M_{5,4}$ -edge spectrum of  $Cp'_3Eu$  resembles that of mixed-valent Sm, Eu, and Tm solids, which have been described as superpositions of  $Ln^{3+}$  and  $Ln^{2+}$  subspectra.<sup>68</sup> Qualitatively, the presence of features attributable to both  $Eu^{2+}$  and  $Eu^{3+}$  configurations in the  $M_{5,4}$ -edge XAS of  $Cp'_3Eu$  provides further support for the existence of  $Cp' \pi \rightarrow 4f$  charge transfer interactions identified by C K-edge spectroscopy. However, the relatively low intensity of the  $Eu^{2+}$  features indicates that the  $Eu^{3+}$  configuration is likely a more dominant component of the ground state for  $Cp'_3Eu$ . The spectrum of  $Cp'_3Eu$  is also distinct from the  $M_{5,4}$ -edge spectra of formally tetravalent Ce and Pr compounds, where the phenomenon of increased charge transfer in the final state causes emergence of satellite features at high energy relative to the main  $M_5$  and  $M_4$  peaks.<sup>75</sup> Theoretical models of  $M_{5,4}$ -edge spectra have been developed for certain f-element systems by using CI calculations,<sup>50,59,72,76–80</sup> but could not be performed at the time of this study due to challenges with incorporating charge transfer in the calculations.<sup>81–83</sup> More detailed theoretical and experimental investigation is needed to determine whether charge transfer satellite peaks are also present, but not resolved, in the  $M_{5,4}$ -edge spectra of  $Cp'_3Eu$  and some other Sm, Eu, and Tm molecules and solids.

Background-subtracted and normalized Eu  $L_3$ -edge XANES spectra of  $Cp'_3Eu$  and reference compounds  $Eu_2O_3$  and  $Cp_2^*Eu$  are shown in Fig. 4. The spectra for  $Cp'_3Eu$  and  $Eu_2O_3$  were similar in that both had the same white-line energy (6981.7 eV). However,  $Cp'_3Eu$  also exhibited a lower energy shoulder at ca. 6974 eV, which is similar to the white-line energies for  $Cp_2^*Eu$  (6975 eV) and other  $Eu^{2+}$  compounds.<sup>84,85</sup> The presence of two features in the Eu  $L_3$ -edge spectrum of  $Cp'_3Eu$  is reminiscent of the Yb  $L_3$ -edge spectra of Yb organometallic complexes<sup>19–21</sup> and the  $L_3$ -edge spectra of tetravalent Ce, Pr, and Tb compounds, which show a low-energy feature that is attributable to a charge-transfer configuration.<sup>59</sup> In analogy to these studies, we described the ground-state electronic structure of  $Cp'_3Eu$  with a CI model involving mixing between  $4f^65d^0$  and  $4f^7\bar{L}5d^0$  configurations. Then, at the Eu  $L_3$ -edge, transitions occur to  $4f^65d^1$  and  $4f^7\bar{L}5d^1$  final states, respectively. Based on this model, the low energy feature in the Eu  $L_3$ -edge spectrum of  $Cp'_3Eu$  was attributed to a  $4f^7\bar{L}5d^0 \rightarrow 4f^7\bar{L}5d^1$  transition, and the main white-line feature was assigned to a  $4f^65d^0 \rightarrow 4f^65d^1$ . The ca. 6 eV peak separation was attributed to the difference in the number of 4f electrons that are available to screen the 5d electron from the Ln 2p core hole. The relative amount of  $4f^7\bar{L}5d^0$  in the ground state was determined at 28(4)% by curve-fitting the spectrum (see Fig. S12 in the ESI†), which indicated that significant charge-transfer interactions are present  $Cp'_3Eu$

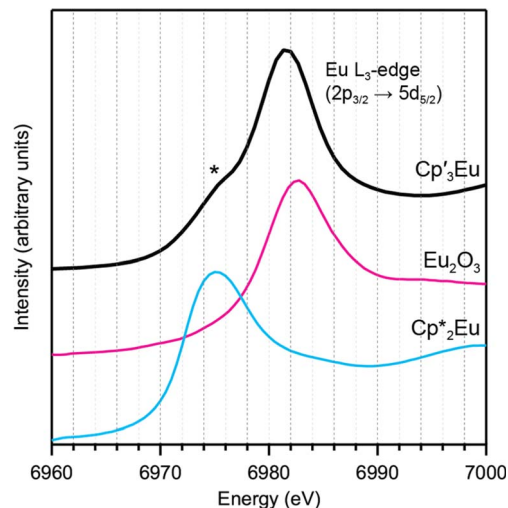


Fig. 4  $L_3$ -edge spectrum for  $Cp'_3Eu$  (magenta) and references for  $Eu^{3+}$  ( $Eu_2O_3$ , dashed black) and  $Eu^{2+}$  ( $Cp_2^*Eu$ , dashed blue). A curve fit of the experimental data for  $Cp'_3Eu$  is provided in the ESI† (Fig. S12†). A shoulder associated with  $Eu^{2+}$  character in the  $L_3$ -edge spectrum for  $Cp'_3Eu$  is highlighted with an asterisk.

$Yb L_3$ -edge XAS for were measured for comparison (see Fig. S13 in the ESI†), which indicated that the relative contribution of the corresponding  $4f^{14}\bar{L}5d^0$  configuration to the ground-state was 0.11(3). The relative amount of  $4f^7\bar{L}5d^0$  in the ground state, 0.28(4), is also referred to as  $n_f$ , the amount of additional 4f character introduced due to covalent bonding.

### Magnetometry

Variable-temperature magnetic susceptibility data for  $Cp'_3Eu$  reported previously by Meihaus *et al.* (Fig. 5) was examined for evidence of charge transfer interactions.<sup>86</sup> At low temperature,  $Cp'_3Eu$  displays temperature independent paramagnetism (TIP) with  $\chi$  equal to 0.13  $emu mol^{-1}$ . At temperatures greater than  $\sim 10$  K, the value of  $\chi$  decreases as the first excited state becomes populated. Qualitatively, the magnetic susceptibility of an

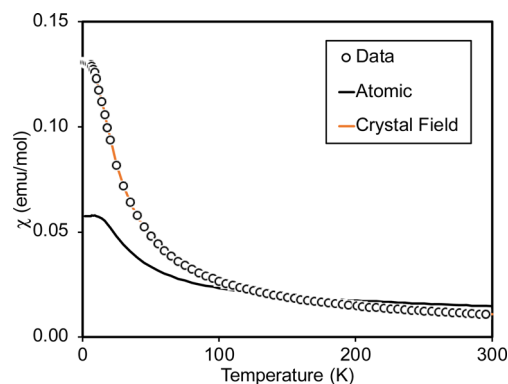


Fig. 5 Magnetic susceptibility of  $Cp'_3Eu$  (open circles). The fit using eqn (4) (free-ion model) is shown as a solid black line. The results of fitting the data using CONDON 3 (crystal field model with  $k = 0.7$ ) is shown using an orange line.



isolated  $\text{Eu}^{3+}$  ion is straightforward. For a free  $\text{Eu}^{3+}$  cation, the term  ${}^7F$  is split by spin-orbit coupling into seven states,  ${}^7F_J$ , with  $J = 0-6$ . The energies of the states ( $E_J$ )<sup>87,88</sup> are:

$$E_J = \frac{\lambda}{2}[J(J+1)] \quad (3)$$

where  $\lambda$  is the spin-orbit coupling constant, which is  $220 \text{ cm}^{-1}$  ( $316 \text{ K}$ ) for a free  $\text{Eu}^{3+}$  ion.<sup>89</sup> Using a free-ion model of the electronic structure of  $\text{Eu(III)}$ , the magnetic susceptibility of a  $\text{Eu}^{3+}$  ion may be calculated using van Vleck' theorem (eqn (4)):<sup>87,88,90</sup>

$$\chi = \frac{\sum_{J=0}^{J=6} \chi_J(2J+1)e^{-E_J/k_B T}}{\sum_{J=0}^{J=6} (2J+1)e^{-E_J/k_B T}} = \frac{N\mu_B^2}{Z} \left( \frac{A}{3\lambda} \right) \quad (4)$$

where:

$$A = 24 + \left( 13.5 \frac{\lambda}{k_B T} - 1.5 \right) e^{\frac{-\lambda}{k_B T}} + \left( 67.5 \frac{\lambda}{k_B T} - 2.5 \right) e^{\frac{-3\lambda}{k_B T}} + \left( 189 \frac{\lambda}{k_B T} - 3.5 \right) e^{\frac{-6\lambda}{k_B T}} + \left( 405 \frac{\lambda}{k_B T} - 4.5 \right) e^{\frac{-10\lambda}{k_B T}} + \left( 742.5 \frac{\lambda}{k_B T} - 5.5 \right) e^{\frac{-15\lambda}{k_B T}} + \left( 1228.5 \frac{\lambda}{k_B T} - 6.5 \right) e^{\frac{-21\lambda}{k_B T}} \quad (5)$$

and

$$Z = 1 + 3e^{-\lambda/k_B T} + 5e^{-3\lambda/k_B T} + 7e^{-6\lambda/k_B T} + 9e^{-10\lambda/k_B T} + 11e^{-15\lambda/k_B T} + 13e^{-21\lambda/k_B T} \quad (6)$$

At low temperature, only the  ${}^7F_0$  orbital-singlet state is populated. This state displays temperature independent magnetism. As the temperature increases, the low-lying  ${}^7F_1$  and  ${}^7F_2$  excited states will be thermally populated, at which point the magnetic susceptibility,  $\chi$ , becomes temperature dependent and starts to decrease.

However, the details of the magnetic susceptibility of  $\text{Cp}'_3\text{Eu}$  are not congruent with this free-ion treatment; both the  $\chi$  value at  $300 \text{ K}$  and  $\chi_{\text{TIP}}$  at low temperatures are larger than the values for the free  $\text{Eu}^{3+}$  cation and reported monomeric  $\text{Eu(III)}$  compounds. Both observations indicate that the lowest lying excited state is much lower in energy than typical for a  $\text{Eu(III)}$  complex.<sup>87,88,91-96</sup> Attempts to fit these data to a free-ion model using eqn (2) resulted in a very small  $\lambda$  value of  $23 \text{ K}$  which is an order of magnitude smaller than reported values for  $\text{Eu(III)}$  compounds ( $\lambda = 250-350 \text{ K}$ ) and is not realistic.<sup>87,88,91-96</sup> The free ion model fails due to its implicit assumption that the splitting of the  $J$  states by the crystal field is much smaller than the spin orbit coupling constant. The XAS results show that the ground state of  $\text{Cp}'_3\text{Eu}$  has a large contribution from a CT state,  $4f^7L_5d^0$ , due to mixing between the  $\text{Eu } 4f$  orbitals and the  $\text{Cp}'$  orbitals with  $a'$  symmetry. The magnitude of this interaction suggests that the splitting of the energies of the  $4f$ -orbitals (and the  $J$  states) may be large enough to affect the variable temperature magnetic susceptibility of  $\text{Cp}'_3\text{Eu}$

To examine this possibility, the magnetic susceptibility of  $\text{Cp}'_3\text{Eu}$  was modeled with crystal field theory using the program

CONDON 3.<sup>97</sup> The crystal field parameters  $B_0^2$ ,  $B_0^4$ ,  $B_0^6$ , and  $B_6^6$  were allowed to vary while spin-orbit coupling ( $\zeta$ ) and Slater repulsion were fixed at their starting values. In comparison to the crystal field parameters, the Slater parameters and  $\zeta$  are less strongly affected by the ligands. Fits were also performed while allowing  $\zeta$  to vary, but doing so increased the value of reduced chi-squared,  $\chi_r^2$ , which indicates that the models with  $\zeta$  fixed at  $1336 \text{ cm}^{-1}$  better reproduced the data. The initial fit of the susceptibility reproduced the data well, but yielded crystal field parameters with values around  $10^4 \text{ cm}^{-1}$ , which are not reasonable due to the small overlap between the  $4f$  and ligand orbitals. Since the XAS measurements indicated considerable mixing between the  $4f$  and ligand orbitals, the effect of decreasing the Stevens orbital reduction parameter,  $k$ , were examined. This parameter corrects the calculated magnetic susceptibility for the decrease in orbital angular momentum due to mixing of the metal orbital with the ligand orbitals. Allowing  $k$  to vary during fits of the magnetic susceptibility provided reasonable quality fits over a large range of  $k$  values, from  $0.55$  to  $0.95$  – suggesting that  $k$  has a relatively flat  $\chi_r^2$  profile – but often provided unrealistically large crystal field parameters. Hence, the value of  $k$  was set to  $0.7$  based on the  $n_f$  value determined by fitting the  $L_3$ -edge data using the relationship  $k = 1 - n_f$ . This provided reasonable crystal field parameters with magnitudes on the order of  $10^3 \text{ cm}^{-1}$ , which agree well with those reported previously by optical spectroscopy and magnetic measurements (Table 1).<sup>98,99</sup>

Fig. 6 compares the energies of the low-lying  $4f^6$  states calculated by CONDON 3 during the fit to the energies of the free-ion states, which were determined by setting  $B_0^2$ ,  $B_0^4$ ,  $B_0^6$ , and  $B_6^6$  to small values. Using Fig. 6, one can understand both the magnetic behavior of  $\text{Cp}'_3\text{Eu}$  and why the free ion model fails to reproduce the magnetic susceptibility. In the absence of a crystal field, the energy of the first excited state,  ${}^7F_1$ , is  $378 \text{ cm}^{-1}$  above the ground state,  ${}^7F_0$ . The crystal field splits  ${}^7F_1$ . The  $m_J = \pm 1$  doublet state is destabilized, and the  $m_J = 0$  singlet state is stabilized such that it is only  $25 \text{ cm}^{-1}$  above the ground state. Because the first excited state is at low energy, the value of  $\chi_{\text{TIP}}$  is much larger than it is in the free ion ( $\chi_{\text{TIP}}$  is inversely

Table 1 Values of parameters used to fit the magnetic susceptibility of  $\text{Cp}'_3\text{Eu}$

Parameter	Model	
	Atomic	Crystal field
$k$		$0.7^a$
$l$ ( $\text{cm}^{-1}$ )	14	$223^a$
$n_f(1-k)$	0	0.3
$B_0^2$ ( $\text{cm}^{-1}$ )		$-2710$
$B_0^4$ ( $\text{cm}^{-1}$ )		$2349$
$B_0^6$ ( $\text{cm}^{-1}$ )		$1917$
$B_6^6$ ( $\text{cm}^{-1}$ )		$-5970$
$\chi_n^{2b}$	6.9	0.0021

<sup>a</sup> Fixed parameter.

$$^b \chi_r^2 = \frac{1}{(\text{num. of data} - \text{num. of parameters})} \sum_i \frac{(\chi_{\text{meas}} - \chi_{\text{calc}})^2}{(\chi_{\text{meas}})^2}$$



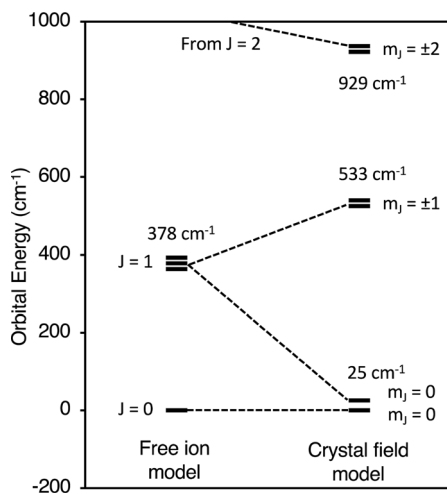


Fig. 6 Low lying states of  $\text{Cp}'_3\text{Eu}$  described using an atomic model and a crystal field model with  $k = 0.7$ .

proportional to the energy gap). In addition, because the first excited state is at low energy, it becomes thermally populated at low temperatures, which results in a rapid decrease in the magnetic susceptibility of  $\text{Cp}'_3\text{Eu}$  as the temperature increases above  $\sim 10$  K. In the free ion model (eqn (4)–(6)), the only way to decrease the energy of the first excited state is to decrease  $\lambda$  to a small value, which is not physically meaningful. Even this is not sufficient to model the magnetic susceptibility since the first excited state in the free ion model is a triplet while the first excited state is actually a singlet.

The fact that reasonable values of  $B_0^2$ ,  $B_0^4$ ,  $B_0^6$ , and  $B_6^6$  could only be obtained when  $k \leq 0.75$  indicates that a large degree of orbital mixing is present in  $\text{Cp}'_3\text{Eu}$ . The nature of this interaction can be evaluated from the experimentally derived MO diagram shown in Fig. 7, which was determined by using the crystal field parameters to calculate the splitting of the 4f orbitals. The MO diagram for  $\text{Cp}'_3\text{Eu}$  resembles that previously reported for  $\text{Cp}'_3\text{Nd}$  (ref. 100) and the qualitative MO diagram shown in Fig. 1. In these cases, one 4f-orbital is more strongly destabilized due to interaction with the ligands, and the other six 4f orbitals are similar in energy suggesting little interaction with the ligand orbitals.

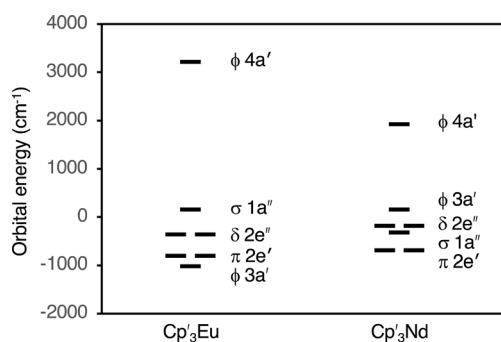


Fig. 7 Experimentally derived MO diagram showing the valence 4f-orbitals for  $\text{Cp}'_3\text{Eu}$  and  $\text{Cp}'_3\text{Nd}$ .

The results from fitting the magnetic susceptibility also illustrate a drawback of this technique, which is that the crystal field model used by CONDON 3 may have multiple sets of parameters that can fit the data well. For this reason, it is helpful to have results from other physical measurements to better constrain the fit. Ideally, one would like to include the energies of the excited states and fit those along with the magnetic susceptibility. Here, we have adopted a different approach and have used the value of  $n_f$  determined from XAS measurements to determine the value of  $k$  in the crystal field model, 0.7.

## Conclusion

In summary, the X-ray spectroscopic and magnetic measurements described above have demonstrated how 4f orbital mixing can increase the magnetic susceptibility of a trivalent Eu organometallic complex,  $\text{Cp}'_3\text{Eu}$ . Despite inducing very different core-hole potentials, the C K-edge, Eu  $M_{5,4}$ -edge, and Eu  $L_3$ -edge XAS measurements each provided evidence for C 2p and Eu 4f orbital mixing. The C K-edge XAS and TDDFT calculations also showed that C 2p and Eu 4f orbital mixing occurs specifically in the orbitals of  $a'$  symmetry ( $4f-\pi$ ). The amount of charge transfer was expressed using a CI model in terms of the relative contribution of the  $|4f^7L\rangle$  configuration to the total ground-state wavefunction. The amount of charge transfer determined by fitting of the Eu  $L_3$ -edge spectrum, 0.28(4), was used to determine the Stevens orbital reduction parameter,  $k$ , used in the modeling of the magnetic susceptibility data. The results of crystal field modeling show that the increased magnetic susceptibility of  $\text{Cp}'_3\text{Eu}$  at low temperature is due to the presence of a low-lying  $m_j = 0$  excited state resulting from the splitting of the  ${}^7F_1$  term. The qualitative MO diagram produced by modeling the magnetic susceptibility data is in excellent agreement with the results of the XAS studies.

In the closely related molecule  $\text{Cp}_3\text{Yb}$ , the presence of orbital mixing in  $\text{Cp}_3\text{Yb}$  is manifested by a 12% contribution of the  $\text{Yb}^{2+}$  charge transfer configuration ( $4f^{14}L$ ) to the ground-state, with the remaining 88% from the ionic,  $\text{Yb}^{3+}$  configuration ( $4f^{13}$ ).<sup>39</sup> The enhancement in charge transfer for  $\text{Cp}'_3\text{Eu}$  compared to  $\text{Cp}_3\text{Yb}$  is consistent with predictions by Denning and coworkers<sup>39</sup> based on the 0.44 eV lower energy of the ligand to metal charge transfer transition for  $\text{Eu}^{3+}$  vs.  $\text{Yb}^{3+}$ .<sup>44</sup> It is also likely to be a general result when comparing isomorphous  $\text{Eu}^{3+}$  and  $\text{Yb}^{3+}$  complexes owing to the lower reduction potential for  $\text{Eu}^{3+}$  ( $-0.34$  V) compared with  $\text{Yb}^{3+}$  ( $-1.05$  V) ions.<sup>101</sup> To explore the limits of this trend, we are currently studying complexes with the related ions  $\text{Sm}^{3+}$  and  $\text{Tm}^{3+}$ , as well as  $\text{Nd}^{3+}$  and  $\text{Dy}^{3+}$ , which may be able to access either  $4f^{n+1}$  or  $4f^{n+1}5d^1$  charge transfer configurations depending on the coordination environment.<sup>58,102</sup>

## Data availability

The data supporting this article have been included as part of the ESI.†



## Author contributions

Conceptualization and project administration: S. G., Y. Q., P. S., C. B., W. D., W. E., W. L., S. M. Formal analysis: S. G., Y. Q., P. S., L. M., C. B., W. D., W. E., W. L., S. M. Investigation: S. G., Y. Q., P. S., A. D., L. M., T. S., C. B., W. D., W. L., S. M. Resources: S. C., D. H., W. E. Validation: S. G., P. S. Funding acquisition and supervision: P. A., C. B., W. D., W. E., W. L., S. M. Writing – original draft: S. G., Y. Q., P. S., W. L., S. M. Writing – reviewing & editing: all authors.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- R. Sessoli and A. K. Powell, *Coord. Chem. Rev.*, 2009, **253**, 2328–2341.
- J. D. Rinehart and J. R. Long, *Chem. Sci.*, 2011, **2**, 2078–2085.
- N. F. Chilton, C. A. P. Goodwin, D. P. Mills and R. E. P. Winpenny, *Chem. Commun.*, 2015, **51**, 101–103.
- K. L. M. Harriman and M. Murugesu, *Acc. Chem. Res.*, 2016, **49**, 1158–1167.
- M. Briganti, E. Lucaccini, L. Chelazzi, S. Ciattini, L. Sorace, R. Sessoli, F. Totti and M. Perfetti, *J. Am. Chem. Soc.*, 2021, **143**, 8108–8115.
- N. Mahieu, J. Piatkowski, T. Simler and G. Nocton, *Chem. Sci.*, 2023, **14**, 443–457.
- A. Ramanathan, J. Kaplan, D. C. Sergentu, J. A. Branson, M. Ozerov, A. I. Kolesnikov, S. G. Minasian, J. Autschbach, J. W. Freeland, Z. G. Jiang, M. Mourigal and H. S. La Pierre, *Nat. Commun.*, 2023, **14**, 1–11.
- U. J. Williams, B. D. Mahoney, P. T. DeGregorio, P. J. Carroll, E. Nakamaru-Ogiso, J. M. Kikkawa and E. J. Schelter, *Chem. Commun.*, 2012, **48**, 5593–5595.
- L. Ungur, J. J. Le Roy, I. Korobkov, M. Murugesu and L. F. Chibotaru, *Angew. Chem., Int. Ed.*, 2014, **53**, 4413–4417.
- F. Gendron, B. Pritchard, H. Bolvin and J. Autschbach, *Dalton Trans.*, 2015, **44**, 19886–19900.
- F.-S. Guo, B. M. Day, Y.-C. Chen, M.-L. Tong, A. Mansikkamäki and R. A. Layfield, *Angew. Chem., Int. Ed.*, 2017, **56**, 11445–11449.
- C. A. P. Goodwin, F. Ortu, D. Reta, N. F. Chilton and D. P. Mills, *Nature*, 2017, **548**, 439–442.
- G. M. Risica, V. Vieru, B. O. Wilkins, T. P. Latendresse, J. H. Reibenspies, N. S. Bhuvanesh, G. P. Wylie, L. F. Chibotaru and M. Nippe, *Angew. Chem., Int. Ed.*, 2020, **59**, 13335–13340.
- M. Tricoire, L. Münzfeld, J. Moutet, N. Mahieu, L. La Droite, E. Moreno-Pineda, F. Gendron, J. D. Hilgar, J. D. Rinehart, M. Ruben, B. Le Guennic, O. Cador, P. W. Roesky and G. Nocton, *Chem.–Eur. J.*, 2021, **27**, 13558–13567.
- L. Münzfeld, M. Dahlen, A. Hauser, N. Mahieu, S. K. Kuppusamy, J. Moutet, M. Tricoire, R. Köppe, L. La Droite, O. Cador, B. Le Guennic, G. Nocton, E. Moreno-Pineda, M. Ruben and P. W. Roesky, *Angew. Chem., Int. Ed.*, 2023, **62**, e202218107.
- T. Jo and A. Kotani, *Phys. Rev. B*, 1988, **38**, 830–833.
- J. M. Veauthier, E. J. Schelter, C. J. Kuehl, A. E. Clark, B. L. Scott, D. E. Morris, R. L. Martin, J. D. Thompson, J. L. Kiplinger and K. D. John, *Inorg. Chem.*, 2005, **44**, 5911–5920.
- C. H. Booth, M. D. Walter, M. Daniel, W. W. Lukens and R. A. Andersen, *Phys. Rev. Lett.*, 2005, **95**, 267202.
- C. H. Booth, M. D. Walter, D. Kazhdan, Y.-J. Hu, W. W. Lukens, E. D. Bauer, L. Maron, O. Eisenstein and R. A. Andersen, *J. Am. Chem. Soc.*, 2009, **131**, 6480–6491.
- C. H. Booth, D. Kazhdan, E. L. Werkema, M. D. Walter, W. W. Lukens, E. D. Bauer, Y.-J. Hu, L. Maron, O. Eisenstein, M. Head-Gordon and R. A. Andersen, *J. Am. Chem. Soc.*, 2010, **132**, 17537–17549.
- G. Nocton, C. H. Booth, L. Maron and R. A. Andersen, *Organometallics*, 2013, **32**, 5305–5312.
- D. Sergentu, C. Booth and J. Autschbach, *Chem.–Eur. J.*, 2021, **27**, 7239–7251.
- N. Magnani, *Int. J. Quantum Chem.*, 2014, **114**, 755–759.
- S. C. Bart, F. W. Heinemann, C. Anthon, C. Hauser and K. Meyer, *Inorg. Chem.*, 2009, **48**, 9419–9426.





- 25 I. Castro-Rodriguez, K. Olsen, P. Gantzel and K. Meyer, *J. Am. Chem. Soc.*, 2003, **125**, 4565–4571.
- 26 D. P. Mills, F. Moro, J. McMaster, J. van Slageren, W. Lewis, A. J. Blake and S. T. Liddle, *Nat. Chem.*, 2011, **3**, 454–460.
- 27 D. M. King, F. Tuna, J. McMaster, W. Lewis, A. J. Blake, E. J. L. McInnes and S. T. Liddle, *Angew. Chem., Int. Ed.*, 2013, **52**, 4921–4924.
- 28 K. R. Meihaus and J. R. Long, *Dalton Trans.*, 2015, **44**, 2517–2528.
- 29 V. Mougel, L. Chatelain, J. Pécaut, R. Caciuffo, E. Colineau, J.-C. Griveau and M. Mazzanti, *Nat. Chem.*, 2012, **4**, 1011–1017.
- 30 Y. Hinatsu, M. Itoh and N. Edelstein, *J. Solid State Chem.*, 1997, **132**, 337–341.
- 31 Y. Hinatsu, M. Wakeshima, N. Edelstein and I. Craig, *J. Solid State Chem.*, 1999, **144**, 20–24.
- 32 L. A. Solola, A. V. Zabula, W. L. Dorfner, B. C. Manor, P. J. Carroll and E. J. Schelter, *J. Am. Chem. Soc.*, 2017, **139**, 2435–2442.
- 33 A. R. Willauer, C. T. Palumbo, F. Fadaei-Tirani, I. Zivkovic, I. Douair, L. Maron and M. Mazzanti, *J. Am. Chem. Soc.*, 2020, **142**, 5538–5542.
- 34 M. J. Daum, A. Ramanathan, A. I. Kolesnikov, S. Calder, M. Mourigal and H. S. La Pierre, *Phys. Rev. B*, 2021, **103**, L121109.
- 35 Y. S. Qiao, H. L. Yin, L. M. Moreau, R. L. Feng, R. F. Higgins, B. C. Manor, P. J. Carroll, C. H. Booth, J. Autschbach and E. J. Schelter, *Chem. Sci.*, 2021, **12**, 3558–3567.
- 36 A. Ramanathan, E. D. Walter, M. Mourigal and H. S. La Pierre, *J. Am. Chem. Soc.*, 2023, **145**, 17603–17612.
- 37 W. W. Lukens, Jr., S. G. Minasian and C. H. Booth, *Chem. Sci.*, 2023, **14**, 12784–12795.
- 38 G. Depaoli, U. Russo, G. Valle, F. Grandjean, A. F. Williams and G. J. Long, *J. Am. Chem. Soc.*, 1994, **116**, 5999–6000.
- 39 M. Coreno, M. de Simone, R. Coates, M. S. Denning, R. G. Denning, J. C. Green, C. Hunston, N. Kaltsoyannis and A. Sella, *Organometallics*, 2010, **29**, 4752–4755.
- 40 R. G. Denning, J. Harmer, J. C. Green and M. Irwin, *J. Am. Chem. Soc.*, 2011, **133**, 20644–20660.
- 41 W. W. Lukens, N. Magnani and C. H. Booth, *Inorg. Chem.*, 2012, **51**, 10105–10110.
- 42 G. Nocton, W. W. Lukens, C. H. Booth, S. S. Rozenel, S. A. Medling, L. Maron and R. A. Andersen, *J. Am. Chem. Soc.*, 2014, **136**, 8626–8641.
- 43 B. M. Day, F.-S. Guo and R. A. Layfield, *Acc. Chem. Res.*, 2018, **51**, 1880–1889.
- 44 P. Dorenbos, *J. Phys.: Condens. Matter*, 2003, **15**, 8417.
- 45 M. T. Trinh, J. C. Wedal and W. J. Evans, *Dalton Trans.*, 2021, **50**, 14384–14389.
- 46 X. Cao and M. Dolg, *J. Mol. Struct.*, 2002, **581**, 139–147.
- 47 S. D. Ramarao, A. K. Singh, U. Subbarao and S. C. Peter, *J. Solid State Chem.*, 2020, **281**, 121048.
- 48 D. N. Huh, J. P. Bruce, S. Ganesh Balasubramani, S. R. Ciccone, F. Furche, J. C. Hemminger and W. J. Evans, *J. Am. Chem. Soc.*, 2021, **143**, 16610–16620.
- 49 S. G. Minasian, J. M. Keith, E. R. Batista, K. S. Boland, D. L. Clark, S. A. Kozimor, R. L. Martin, D. K. Shuh and T. Tylliszczak, *Chem. Sci.*, 2014, **5**, 351–359.
- 50 D. E. Smiles, E. R. Batista, C. H. Booth, D. L. Clark, J. M. Keith, S. A. Kozimor, R. L. Martin, S. G. Minasian, D. K. Shuh, S. C. E. Stieber and T. Tylliszczak, *Chem. Sci.*, 2020, **11**, 2796–2809.
- 51 Y. Qiao, G. Ganguly, C. H. Booth, J. A. Branson, A. S. Ditter, D. J. Lussier, L. M. Moreau, D. R. Russo, D.-C. Sergentu, D. K. Shuh, T. Sun, J. Autschbach and S. G. Minasian, *Chem. Commun.*, 2021, **57**, 9562–9565.
- 52 M. E. Fieser, M. G. Ferrier, J. Su, E. Batista, S. K. Cary, J. W. Engle, W. J. Evans, J. S. Lezama Pacheco, S. A. Kozimor, A. C. Olson, A. J. Ryan, B. W. Stein, G. L. Wagner, D. H. Woen, T. Vitova and P. Yang, *Chem. Sci.*, 2017, **8**, 6076–6091.
- 53 J. W. Lauher and R. Hoffmann, *J. Am. Chem. Soc.*, 1976, **98**, 1729–1742.
- 54 B. E. Bursten and R. J. Strittmatter, *Angew. Chem., Int. Ed.*, 1991, **30**, 1069–1085.
- 55 L. Maron, O. Eisenstein and R. A. Andersen, *Organometallics*, 2009, **28**, 3629–3635.
- 56 W. W. Lukens, N. M. Edelstein, N. Magnani, T. W. Hayton, S. Fortier and L. A. Seaman, *J. Am. Chem. Soc.*, 2013, **135**, 10742–10754.
- 57 T. A. Albright, J. K. Burdett and M. Whangbo, *Orbital Interactions in Chemistry*, John Wiley and Sons, New York, 1985.
- 58 M. E. Fieser, M. R. MacDonald, B. T. Krull, J. E. Bates, J. W. Ziller, F. Furche and W. J. Evans, *J. Am. Chem. Soc.*, 2015, **137**, 369–382.
- 59 S. G. Minasian, E. R. Batista, C. H. Booth, D. L. Clark, J. M. Keith, S. A. Kozimor, W. W. Lukens, R. L. Martin, D. K. Shuh, S. C. E. Stieber, T. Tylliszczak and X.-d. Wen, *J. Am. Chem. Soc.*, 2017, **139**, 18052–18064.
- 60 S. G. Minasian, J. M. Keith, E. R. Batista, K. S. Boland, S. A. Kozimor, R. L. Martin, D. K. Shuh, T. Tylliszczak and L. J. Vernon, *J. Am. Chem. Soc.*, 2013, **135**, 14731–14740.
- 61 E. Ruhl and A. P. Hitchcock, *J. Am. Chem. Soc.*, 1989, **111**, 5069–5075.
- 62 A. T. Wen and A. P. Hitchcock, *Can. J. Chem.*, 1993, **71**, 1632–1644.
- 63 A. T. Wen, E. Ruhl and A. P. Hitchcock, *Organometallics*, 1992, **11**, 2559–2569.
- 64 A. Bianconi, A. Marcelli, H. Dexpert, R. Karnatak, A. Kotani, T. Jo and J. Petiau, *Phys. Rev. B*, 1987, **35**, 806–812.
- 65 H. Dexpert, R. C. Karnatak, J. M. Esteva, J. P. Connerade, M. Gasgnier, P. E. Caro and L. Albert, *Phys. Rev. B*, 1987, **36**, 1750–1753.
- 66 G. Kaindl, G. Schmiester, E. V. Sampathkumaran and P. Wachter, *Phys. Rev. B*, 1988, **38**, 10174–10177.
- 67 B. T. Thole, G. van der Laan, J. C. Fuggle, G. A. Sawatzky, R. C. Karnatak and J. M. Esteva, *Phys. Rev. B*, 1985, **32**, 5107–5118.
- 68 G. Kaindl, G. Kalkowski, W. D. Brewer, B. Perscheid and F. Holtzberg, *J. Appl. Phys.*, 1984, **55**, 1910–1915.



- 69 M. Stavinoha, J. A. Cooley, S. G. Minasian, T. M. McQueen, S. M. Kauzlarich, C. L. Huang and E. Morosan, *Phys. Rev. B*, 2018, **97**, 195146.
- 70 B. T. Thole, G. Vanderlaan, J. C. Fuggle, G. A. Sawatzky, R. C. Karnatak and J. M. Esteve, *Phys. Rev. B*, 1985, **32**, 5107–5118.
- 71 J. B. Goedkoop, B. T. Thole, G. van der Laan, G. A. Sawatzky, F. M. F. de Groot and J. C. Fuggle, *Phys. Rev. B*, 1988, **37**, 2086–2093.
- 72 M. W. Löble, J. M. Keith, A. B. Altman, S. C. E. Stieber, E. R. Batista, K. S. Boland, S. D. Conradson, D. L. Clark, J. Lezama Pacheco, S. A. Kozimor, R. L. Martin, S. G. Minasian, A. C. Olson, B. L. Scott, D. K. Shuh, T. Tyliczszak, M. P. Wilkerson and R. A. Zehnder, *J. Am. Chem. Soc.*, 2015, **137**, 2506–2523.
- 73 T. A. Pham, A. B. Altman, S. C. E. Stieber, C. H. Booth, S. A. Kozimor, W. W. Lukens, D. T. Olive, T. Tyliczszak, J. Wang, S. G. Minasian and K. N. Raymond, *Inorg. Chem.*, 2016, **55**, 9989–10002.
- 74 M. G. Silly, S. Blanchandin, F. Sirotti, F. Lux, S. Chevreux, G. Lemerrier and F. Charra, *J. Phys. Chem. C*, 2013, **117**, 9766–9771.
- 75 A. Kotani and H. Ogasawara, *J. Electron Spectrosc. Relat. Phenom.*, 1992, **60**, 257–299.
- 76 C. Dallera, K. Giarda, G. Ghiringhelli, A. Tagliaferri, L. Braicovich and N. B. Brookes, *Phys. Rev. B*, 2001, **64**, 153104.
- 77 C. Dallera, M. Grioni, A. Shukla, G. Vankó, J. L. Sarrao, J. P. Rueff and D. L. Cox, *Phys. Rev. Lett.*, 2002, **88**, 196403.
- 78 S. M. Butorin, A. Modin, J. R. Vegelius, K. O. Kvashnina and D. K. Shuh, *J. Phys. Chem. C*, 2016, **120**, 29397–29404.
- 79 K. O. Kvashnina, P. M. Kowalski, S. M. Butorin, G. Leinders, J. Pakarinen, R. Bès, H. J. Li and M. Verwerft, *Chem. Commun.*, 2018, **54**, 9757–9760.
- 80 K. O. Kvashnina and S. M. Butorin, *Chem. Commun.*, 2022, **58**, 327–342.
- 81 E. Stavitski and F. M. F. de Groot, *Micron*, 2010, **41**, 687–694.
- 82 R. D. Cowan, *Theory of Atomic Structure and Spectra*, University of California Press, 1981.
- 83 F. M. F. de Groot and A. Kotani, *Core Level Spectroscopy of Solids*, Taylor and Francis, New York, 2008.
- 84 S. Harder, D. Naglav, C. Ruspic, C. Wickleder, M. Adlung, W. Hermes, M. Eul, R. Pottgen, D. Rego, F. Poineau, K. Czerwinski, R. Herber and I. Nowik, *Chem.–Eur. J.*, 2013, **19**, 12272–12280.
- 85 W. Liu, L. Liu, Y. Wang, L. Chen, J. A. McLeod, L. Yang, J. Zhao, Z. Liu, J. Diwu, Z. Chai, T. E. Albrecht-Schmitt, G. Liu and S. Wang, *Chem.–Eur. J.*, 2016, **22**, 11170–11175.
- 86 K. R. Meihaus, M. E. Fieser, J. F. Corbey, W. J. Evans and J. R. Long, *J. Am. Chem. Soc.*, 2015, **137**, 9855–9860.
- 87 Y. Takikawa, S. Ebisu and S. Nagata, *J. Phys. Chem. Solids*, 2010, **71**, 1592–1598.
- 88 M. Andruh, E. Bakalbassis, O. Kahn, J. C. Trombe and P. Porcher, *Inorg. Chem.*, 1993, **32**, 1616–1622.
- 89 G. S. Ofelt, *J. Chem. Phys.*, 1963, **38**, 2171–2180.
- 90 J. H. Van Vleck, *The Theory of Electric and Magnetic Susceptibilities*, Oxford University Press, 1932.
- 91 M.-L. Sun, J. Zhang, Q.-P. Lin, P.-X. Yin and Y.-G. Yao, *Inorg. Chem.*, 2010, **49**, 9257–9264.
- 92 Y. Wan, L. Zhang, L. Jin, S. Gao and S. Lu, *Inorg. Chem.*, 2003, **42**, 4985–4994.
- 93 J. Lhoste, A. Pérez-Campos, N. Henry, T. Loiseau, P. Rabu and F. Abraham, *Dalton Trans.*, 2011, **40**, 9136–9144.
- 94 J. Legendziewicz, V. Tsaryuk, V. Zolin, E. Lebedeva, M. Borzechowska and M. Karbowski, *New J. Chem.*, 2001, **25**, 1037–1042.
- 95 C. Benelli, A. Caneschi, D. Gatteschi, L. Pardi, P. Rey, D. P. Shum and R. L. Carlin, *Inorg. Chem.*, 1989, **28**, 272–275.
- 96 X.-J. Wang, Z.-M. Cen, Q.-L. Ni, X.-F. Jiang, H.-C. Lian, L.-C. Gui, H.-H. Zuo and Z.-Y. Wang, *Cryst. Growth Des.*, 2010, **10**, 2960–2968.
- 97 M. Speldrich, J. van Leusen and P. Kögerler, *J. Comput. Chem.*, 2018, **39**, 2133–2145.
- 98 S. Jank, H. Reddmann and H. D. Amberger, *J. Alloys Compd.*, 1997, **250**, 387–390.
- 99 P. W. Smith, J. Hrubý, W. J. Evans, S. Hill and S. G. Minasian, *J. Am. Chem. Soc.*, 2024, **146**(9), 5781–5785.
- 100 W. W. Lukens, M. Speldrich, P. Yang, T. J. Duignan, J. Autschbach and P. Kögerler, *Dalton Trans.*, 2016, **45**, 11508–11521.
- 101 S. Cotton, *Lanthanide and Actinide Chemistry*, John Wiley and Sons, West Sussex, UK, 2006.
- 102 M. E. Fieser, C. T. Palumbo, H. S. La Pierre, D. P. Halter, V. K. Voora, J. W. Ziller, F. Furche, K. Meyer and W. J. Evans, *Chem. Sci.*, 2017, **8**, 7424–7433.

