Activation of H₂ over the Ru-Zn Bond in the Transition Metal-Lewis Acid Heterobimetallic Species [Ru(IPr)₂(CO)ZnEt]⁺ (IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene)

Ian M. Riddlestone, Nasir A. Rajabi, John P. Lowe, Mary F. Mahon, Stuart A. Macgregor and Michael K. Whittlesey

Department of Chemistry, University of Bath, Claverton Down, Bath BA2 7AY, UK

Institute of Chemical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK

Supporting Information Placeholder

ABSTRACT: Reaction of [Ru(IPr)(CO)ZnEt]BAr⁴⁺ with ZnEt₂ forms the heterobimetallic species [Ru(IPr)₂(CO)ZnEt]BAr⁴⁺ (2) which features an unsupported Ru-Zn bond. Two reactions with H₂ to give [Ru(IPr)₂(CO)(η²-H₂)ZnEt]BAr⁴⁺ (3) and [Ru(IPr)₁(CO)(H₂)ZnEt]BAr⁴⁺ (4). DFT calculations predict that H₂ activation at 2 proceeds via oxidative cleavage at Ru with concomitant hydride transfer to Zn. 2 can also activate hydric H⁻H bonds (E = B, Si) and computed mechanisms for the facile H⁻H exchange processes observed in 3 and 4 are presented.

Metal-ligand cooperation is a widely used strategy for the activation and catalytic transformation of small molecules. Many such systems are predicated on transition metal-Lewis base (TM-LB) combinations, as well as those featuring electronically flexible ligand scaffolds, exemplified by Milstein’s (de)aromatization approach. More recently, TM-LA (LA = Lewis acid) cooperativity has re-emerged with reports of H₂ cleavage, the activation of C-H and more polar E-H bond cleavage, and, in some cases, involvement in catalytic processes. To date such TM-LA cooperation has been dominated by cases where the LA is a B or Al center that is brought into proximity with the TM via a constrained geometry ligand, typically a bi- or polydentate P- or N-based species. Recently, we report on the preparation and reactivity of a novel TM-LA system, [Ru(IPr)(CO)ZnEt]BAr⁴⁺ (1), which features a direct, unsupported Ru-Zn bond and is accessed via the simple addition of ZnEt₂ to [Ru(IPr)(CO)]BAr⁴⁺ (2). Complex 2 can activate H₂ with net addition across the Ru-Zn bond to give [Ru(IPr)(CO)(η²-H₂)ZnEt]BAr⁴⁺ (3). The observation of facile intramolecular H⁻H exchange in 3, along with DFT calculations, highlights the ability of the TM-LA [RuZn] moiety to act as a flexible and reversible hydride shuttle.

In line with the reported electrophilic reactivity of the hydride ligand in [Ru(IPr)(CO)]BAr⁴⁺ (1), addition of one equivalent of ZnEt₂ to a fluorobenzene solution of this species gave the Ru-Zn complex 2 (Scheme 1), which was isolated as a red solid in 76% yield. H⁻¹ NMR spectroscopy confirmed the absence of any hydride ligand in 2 and confirmed the presence of a single ZnEt group on the basis of the 8:3:2 ratio of Pr methine protons to low frequency signals at δ 0.73 (CH₃) and δ -0.11 (CH₂).

Upon shaking a C₆H₅F solution of 2 under H₂ (1 atm), there was an instantaneous color change (deep red to colorless) resulting from the formation of the novel dihydrogen dihydride complex [Ru(IPr)(CO)(η²-H₂)ZnEt]BAr⁴⁺ (3, Scheme 1). The ¹H NMR spectrum of 3 exhibited two hydride resonances, a broad signal at δ -5.33 and a sharp peak at δ -12.13, in a relative ratio of 3:1. Cooling to -28 °C resolved the broad resonance into two signals (relative ratio 2:1) at δ -5.09 and -7.79 (with Tₛ values of 31 and 72 ms respectively) assigned to Ru(η²-H₂) and Ru-H-Zn (trans to CO) respectively. Both signals remained broad, indicative of exchange; this was confirmed by EXY and magnetization transfer experiments (Figure S11). No exchange with the remaining Ru-H-Zn trans to dihydrogen (δ -12.13, Tₛ = 809 ms; Tₘ = 638 ms (CD₂Cl₂, 400 MHz, -41 °C)) was found. However, upon exposure of 3 to 1 atm D₂, ¹H and ²H NMR spectra showed unequivocally that all three sites underwent a slower chemical exchange with deuterium incorporated into the Ru(η²-H₂) and at both Ru-H-Zn positions.

The η²-H₂ ligand in 3 proved hard to dissociate, with only ca. 20% conversion to [Ru(IPr)(CO)(H₂)ZnEt]BAr⁴⁺ (4) apparent even after evaporating a C₆H₅F solution of 3 to complete dryness. In fact, full conversion to 4 required heating a solid sample of 3 at 50 °C under dynamic vacuum for 24 h. Subjeacting solid 3 to vacuum/heat for further time (ca. 72 h) showed that all four hydride ligands could be removed, although reformulation of 2 was also accompanied by additional, unidentified side products. Complex 4 displayed a low frequency (δ -27.06) Ru-H-Zn signal which now exchanged on the NMR timescale (magnetization transfer and EXSY measurements; Figure S12) with a second Ru-H-Zn resonance at δ -3.75.
The molecular structures of the cations in 2, 3 and 4 are shown in Figure 1, along with a comparison with computed data for the central {Ru(H)Zn} moieties in each case (n = 0, 4 and 2 respectively). 2 exhibits a Ru-Zn distance of 2.4069(7) Å, and also features two short Ru–H-C agostic interactions to one of the IPr ligands (Ru(1)-H(27A)-C(27) 2.13(3) Å, Ru(1)-H(27C)-C(27) 2.22(4) Å), similar to those seen previously in 1. In 3 and 4 the η1-Hz and hydride hydrogens were included in the model, the latter being refined without restraint. Both these species have elongated Ru-Zn distances (2.5125(3) Å and 2.4896(4) Å, respectively) and have distinctly asymmetric Ru-H and Zn-H distances (2.5125(3) Å and 2.4896(4) Å, respectively) being refined without restraint. Both these species have elongated Ru-Zn distances as well as the various Ru-H and Zn-H distances in 2, 3 and 4, allowing for the inherent uncertainty in the H atom positions (see Figure 1, right hand side). NBO calculations characterize 2 as a Ru(0) species interacting with a cationic [ZnEt]+ moiety via Ru →Zn σ-donation. In contrast, no significant direct Ru-Zn interaction is seen in either 3 or 4 (see Supporting Information for full details and orbital plots). NPA charges were used to characterize the nature of the hydride ligands. These indicate that the more evenly shared hydrides, H6 (trans to CO in 3 and 4), exhibit a significant negative charge (qH = -0.23 and -0.26 respectively) while this reduces and becomes positive as the hydride moves closer to Ru (H6: qH = -0.07 trans to η1-Hz in 3; qH = +0.05 trans to the agostic in 4). For comparison the terminal hydride in 1 (which lies trans to a vacant site) has qH = +0.16. H6 in 4 therefore more resembles a terminal Ru-hydride: indeed an Atoms in Molecules study on 4 shows the absence of any Zn⋯H6 bond path (Figure S14). The {Ru(H)Zn} moieties in these species are therefore structurally flexible and able to access both bridging and terminal hydride character depending on the precise coordination environment.

Although examples of [M(H)nZn] complexes exist for M = Ru,17 as well as for other late TMs,18 these all result from metal hydride precursors and, to the best of our knowledge, formation via bimetallic M-Zn cleavage of H2 has no precedent.19,20 We have therefore used DFT calculations to study the formation of 2 as well as its onwards reactivity with H2 to 3 and 4. Figure 2 indicates that the initial addition of ZnEt2 to 1 forms an intermediate I(1-2)1 at -12.3 kcal/mol in which the {RuZn} moiety is bridged by both a hydride and an ethyl ligand; the latter also engages in a β-agostic interaction with the Ru center. Ethyl group transfer onto Ru proceeds via TS(1-2)1 with a barrier of 11.1 kcal/mol and is induced by rotation of the {Ru(H)Zn} moiety such that the bridging hydride drops below the equatorial coordination plane. This allows the CO ligand to move trans to the developing Ru-Et ligand (I(1-2)2, G = -13.7 kcal/mol). The bridging hydride can now couple with the adjacent ethyl group via TS(1-2)2 at -6.9 kcal/mol leading, after release of ethane, to the formation of 2 at -30.4 kcal/mol. In this case an alternative isomer of 2 devoid of agostic interactions is located, similar to the situation described previously for 1 for which several isomers were also found.11

Figure 1. Molecular structures of the cations in 2, 3 and 4. Thermal ellipsoids are shown at 30%. All non-hydride and non-agostic hydrogen atoms are omitted for clarity. Also shown are comparisons of the key experimental and (in italics) computed distances around the central {Ru-Zn} moiety, along with the accompanying NBO charges.

Figure 2. Computed reaction profile (free energy, kcal/mol) for the formation of 2 and CH3H2 from 1 and ZnEt2; schematic structures show key distances (Å) within the equatorial plane; [Ru] = Ru(IPr)2+*. An ethane σ-complex, I(1-2)3, generated from TS(1-2)2 is omitted for clarity. *non-agostic isomer of 2 located.
Figure 3 shows one possible mechanism for the reaction of 2 with H₃ to give 3 and 4. Addition of two molecules of H₂ to 2 forms the bis-η²-H₂ intermediate I(2-3)1 at -32.1 kcal/mol. A very flat free energy surface then sees an essentially barrierless cleavage of the H₀-H⁻ ligand with net addition over the Ru-Zn bond to give I(2-3)2 at -34.8 kcal/mol. Rotation about the Ru···Zn vector then allows transfer of H₀ onto Zn to form 3 at -41.4 kcal/mol. H₂ loss from 3 is computed to be kinetically accessible (ΔG° = 15.8 kcal/mol), but endergonic, 4 (+ H₂) lying 5 kcal/mol above 3. This is consistent with the reluctance of this species to lose H₂ found experimentally.

Figure 3. Computed reaction profile (free energy, kcal/mol) for the formation of 3 and 4 from 2; schematic structures show key distances (Å) in the equatorial plane, as well as the labeling scheme for the H atoms; [Ru] = Ru(IPr)²⁺. Inset: geometry of H₂ activation transition state TS(2-3)1 (IPr ligands omitted).

The computed structure of the key H₂ activation transition state TS(2-3)1 (inset, Figure 3) exhibits an elongated H₀-H⁻ moiety (1.19 Å cf. 0.91 Å in I(2-3)1). At this point the Zn···H₀ distance of 2.16 Å implies little, if any, interaction with the Zn center and it is only after the cleavage that the Zn participates by accepting a hydride ligand. In addition, minimal polarization of the H₀-H⁻ bond is computed in the transition state (q_H₀ = +0.05; q_H⁻ = +0.02). We therefore propose that H₂ activation occurs via oxidative cleavage mediated by Ru, followed by hydride transfer to Zn. In support of Ru being the key player in the H₂ cleavage, the activation of H₀-H⁻ trans to Zn in I(2-3)1 was also characterized: this proceeds via a structurally similar transition state at -28.6 kcal/mol which leads to a Ru(η²-H₂)H₂ complex in which the Zn is unable to accept either hydride (Figure S17).

The mechanisms of H/H exchange in 3 and 4 have also been modelled. For 3, exchange occurs both between the η²-H₂ ligand and the cis bridging hydride (H₀/H₃ exchange) as well as between the two chemically distinct bridging hydrides (H₀/H₃ exchange). H₀/H₃ exchange can proceed via the mechanism in Figure 3, with reversible formation of the bis-η²-H₂ complex I(2-3)1 and rotation of the H₀-H⁻ ligand. The latter occurs via a transition state at -28.3 kcal/mol, giving an overall exchange barrier of 13.1 kcal/mol. For H₀/H₃ exchange a σ-CAM process was characterized that sees formation of the H₀/(η²-H₂-H⁻) complex, I(3-3)² (Figure 4a). H₀-H⁻ rotation and reversing the σ-CAM completes the exchange, the rotation transition state being the highest point in this process and equating to an overall barrier of 9.8 kcal/mol. The lower barrier for H₀/H₃ exchange is consistent with the EXSY experiments that indicated that only that process proceeded on the NMR timescale. H₂/H₃ exchange in 4 proceeds by a similar mechanism to that in 3 (Figure 4b). Thus initial rotation about the Ru···Zn vector cleaves the Zn-H₀ bond and forms I(4-4)1; H₀ can then transfer onto H₃ to form the η²-H₀-H⁻ complex I(4-4)². H₀ rotation and reversing these processes complete the exchange. The highest transition states in this process are at -22.9 kcal/mol and correspond to an overall barrier of 13.5 kcal/mol. In principle, movement of the CO ligand from trans to H₃ to trans to H₀ would also render these two sites equivalent. However, this process has a barrier of 31.5 kcal/mol as it passes through a symmetrical Y-shaped [RuCO(H₂)] moiety, which is strongly disfavored for a σ'' configuration.

Figure 4. Computed mechanisms (free energy, kcal/mol) for (a) H₀/H₃ in 3 and (b) H₀/H₃ in 4; [Ru] = Ru(IPr)²⁺. Transition state energies for each step are given in square brackets.

To probe whether other E-H bonds could add across the Ru-Zn bond in 2, preliminary investigations with both protic and hydridic reagents have been undertaken. NH₃ simply coordinated to form the ammonia complex [Ru(IPr)²⁺(CO)(NH₃)ZnEt]BAR²⁺ (3; Figure S13). With HBcat and PhSiH₃, room temperature dehydrogenation took place to give 3 as the major ruthenium-containing product of both reactions. Surprisingly, even a 1:1 ratio of 2:HBcat generated hydride signals characteristic of 3 suggesting that a strong driving force exists for formation of the Ru(H₃)Zn moiety.¹¹B NMR spectroscopy confirmed the formation of Bcat(δ 31), but also showed a second major product at δ 22 which, by comparison to the literature, appears to be B₂cat.²³ In the reaction of 2 with PhSiH₃,²⁵Si NMR spectroscopy showed that PhSiH and Ph₂SiH were the major silicon containing reaction products, although a number of other, lower intensity signals were also present which we believe arise from the presence of three reactive Si-H bonds in the starting material, as well as the need for SiH₄ formation for atom balance. There is a clear silane dependence to this chemistry since no reaction was seen between 2 and either
PhSiH₃ or PhMe₂SiH. Further studies are required to elucidate the pathways of the borane/silane dehydrogenation reactions.

In conclusion, we have described the facile formation of the TM-LA heterobimetallic species, 2, featuring an unconstrained and unsupported Ru-Zn bond. This species is a rare example of an active TM-LA system derived from a non-group 13 element LA: and unsupported Ru-Zn bond. This species is a rare example of a (reversible) hydride acceptor. H/H exchange experiments and calculations on 3 and 4 show that intermediates with unsupported Ru-Zn bonds retain kinetic accessibility even after H₂ addition. This, along with the observation of the activation of hydric E-H bonds (E = B, Si), suggests that such unconstrained heterobimetallic TM-LA species may have potential applications in catalysis and this possibility is being pursued in our laboratories.

ASSOCIATED CONTENT
Supporting Information

All data supporting this study are provided as Supporting Information accompanying this paper. This includes: synthesis, characterization (inc. multinuclear NMR spectra) and crystallographic data (CIF) for 2-5; computational data, including computed geometries and energies, details of alternative reaction pathways and a molecular graph of 4. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Authors

s.a.macgregor@hw.ac.uk; m.k.whittlesey@bath.ac.uk

Notes

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REFERENCES

(2) In CDCl₃, a T value of 47 ms was measured for the Ru-H-Zn resonance at 8-7.79-8.28 °C. The value increased upon cooling: 93 ms at -41 °C. 205 ms at -55 °C and 323 ms at -68 °C.

In conclusion, we have described the facile formation of the {Ru(H)₂Zn} species and {Ru(H)Zn} moiety, the half-arrow formalism (Green, J. C.; Green, M. J. H. Coord. Chem. Rev. 2016, 314, 71.).

Heterobimetallic Ru-Zn Complexes
Transition Metal Lewis Acid Cooperativity
DFT Calculations