ORGANOMETALLICS

Article

pubs.acs.org/Organometallics

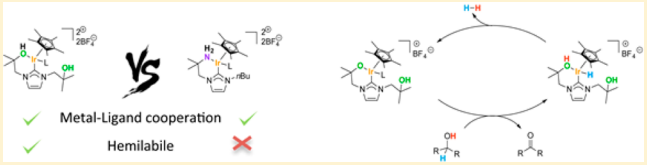
Acceptorless Alcohol Dehydrogenation: OH vs NH Effect in Bifunctional NHC–Ir(III) Complexes

Greco González Miera,[†] Elisa Martínez-Castro,[†] and Belén Martín-Matute*

Department of Organic Chemistry, Stockholm University, Stockholm SE-10691, Sweden

Supporting Information

ABSTRACT: Bifunctional complexes bearing N-heterocyclic carbene (NHC) ligands functionalized with hydroxy or amine groups were synthesized to measure the beneficial effect of different modes of metal–ligand cooperation in the acceptorless dehydrogenation of alcohols. In comparison to complexes with an amine moiety, hydroxy-functionalized iridium catalysts showed superior activity. In contrast to alcohols, 1,4-diols underwent cyclization to give the corresponding tetrahydrofurans without involving dehydrogenation processes. Mechanistic investigations to rationalize the "OH effect" in these types of complexes have been undertaken.



INTRODUCTION

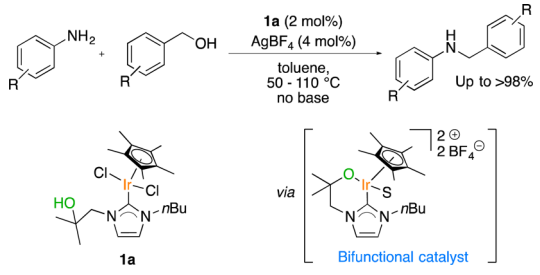
Bifunctional transition-metal complexes, having two or more active sites (i.e., a transition-metal center and a functional group that can be engaged in protonation/deprotonation steps), have given excellent results in terms of activity and selectivity in numerous catalytic transformations.[1] Bifunctional ligands not only influence the steric and electronic properties of transition-metal complexes but also affect the mechanistic pathway through chemical interaction with substrates and products.

There are two conceptually different families of bifunctional complexes: those whose participating functional group is in the first coordination sphere of the metal center,[1a] and those in which this functional group is not directly bound to the metal center.[2] This latter type leads to so-called remote metal–ligand cooperation.[3−5] In both cases, the ligands participate in reversible proton-transfer steps, while at the same time the metal is involved in other elementary steps in the catalytic transformation, commonly in hydride-transfer processes.[1] The synergistic effect of bifunctional complexes of the first type was first demonstrated by Noyori with a ruthenium complex bearing an ethylenediamine ligand.[6,7] From these early examples, many reports of this type of metal–ligand cooperative catalysis have been published.[6a,8,9] Interestingly, the vast majority of these reports are based on ligands bearing nitrogen donor atoms giving rise to an "NH effect" in bifunctional catalysis.[1c,2]

Examples where the cooperation relies on oxygen-containing active sites in the first coordination sphere have been much less common.[4−17] This could be due to the fact that, for late transition metals, coordination with hydroxy moieties is weaker than coordination with amine functional groups. Amine-containing bifunctional complexes have been used as catalysts in a vast number of hydrogen-transfer processes.[9g,18] These complexes usually follow a concerted outer-sphere mechanism involving a six-membered transition state.[1a] On the other hand, the hemilabile behavior of bifunctional complexes with alcohol/alkoxide moieties allows both inner- and outer-sphere mechanisms as a result of the weaker metal–oxygen interaction.[11,12,14,15] This opens up an alternative to the coordinatively more rigid bidentate or pincer ligands that show the "NH effect".

NHC (N-heterocyclic carbene) ligands have played a significant role on the design of bifunctional metal complexes for catalytic applications. In a recent review article,[19] Peris describes them as "smart" ligands, since they can be "*switchable, multifunctional, adaptable and tuneable*". As part of our current research into the development of efficient catalytic processes, we have also investigated the catalytic activity of a bifunctional Ir(III) complex bearing an NHC ligand functionalized with a hydroxy active site (**1a**; Scheme 1).[14a] The activity of **1a** was demonstrated in the alkylation of amines with alcohols under mild conditions. Importantly, the addition of an external base was not needed, since the bifunctional tethered alcohol participated in the protonation/deprotonation steps, through both inner- and outer-sphere pathways.[14b] A related complex

Scheme 1. N-Alkylation of Amines with Alcohols Catalyzed by a Bifunctional NHC–Ir(III) Catalyst



Special Issue: Organometallic Chemistry in Europe

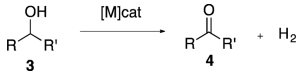
Received: March 24, 2017

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX–XXX

was also immobilized into a metal−organic framework (MOF), and the beneficial cooperative behavior of the Ir−alcohol/alkoxide complex was demonstrated here in the isomerization of allylic alcohols, a reaction that also involves hydride- and proton-transfer steps.[20] The enhanced catalytic activity observed for bifunctional complexes of this type, attributed to the alcohol/alkoxide functionality, and so termed an "OH effect", may be dual in nature: (1) the oxidation of polar bonds takes place through a concerted transfer of hydride and proton to the metal center and the alkoxy functionality, respectively, and (2) unlike bifunctional NH ligands, OH ligands are able to provide available coordination sites on the metal center upon decoordination.

The oxidation of alcohols (**3**) by dehydrogenation is a conceptually different reaction (Scheme 2).[21] This is an atom-economical oxidation that does not require hydrogen acceptors. Instead, molecular hydrogen is released, adding a positive entropic contribution to this endothermic process.[22] The reaction is currently significant, as it provides a source of liquid organic hydrogen carriers that could be implemented using liquid fuel infrastructure in the proposed incoming "hydrogen economy".[23] Acceptorless alcohol dehydrogenation (AAD) offers also significant advantages in organic chemistry for the synthesis of carbonyl-containing building blocks (**4**) from the corresponding alcohols, avoiding the use of oxidants and facilitating purification procedures. AAD reactions have progressed significantly in recent years.[21a,24] The number of recent reports of AAD reactions, involving homogeneous complexes of Ru,[25] Ir,[26] Rh,[27] Os,[28] Fe,[29] Co,[30] Cu,[31] and Ni,[13] among others, and even heterogeneous Pd nanoparticles supported in MOFs[32] or Ru nanoparticles supported on alumina,[33] underlines the importance of research into atom-economical processes that avoid the use of harmful oxidizing agents.

Scheme 2. Acceptorless Alcohol Dehydrogenation



In this paper, we report the catalytic activity of a family of NHC−Ir(III) complexes in acceptorless alcohol dehydrogenation reactions. Surprisingly, we found that complexes with bifunctional ligands bearing weakly coordinating hydroxy active sites showed activity significantly higher than those with amine groups. The scope of the reaction to prepare carbonyl compounds from alcohols has been investigated. Mechanistic investigations to understand the "OH effect" of these types of bifunctional catalysts in AAD processes were also undertaken.

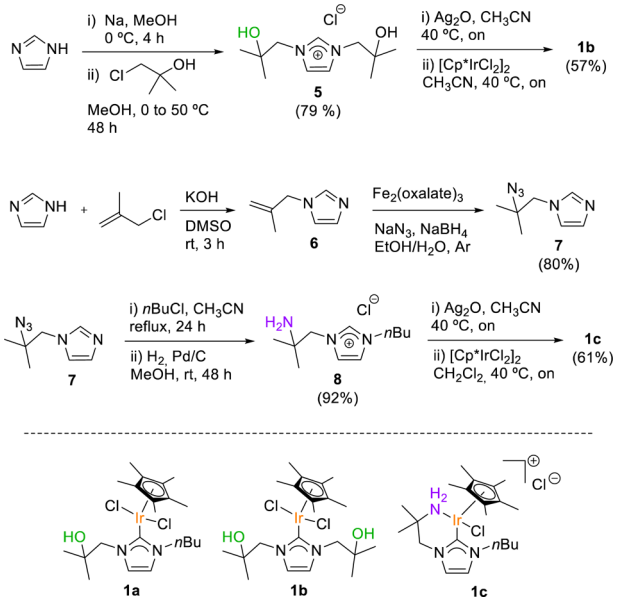
RESULTS AND DISCUSSION

Synthesis of Iridium Complexes. Iridium(III) complex **1a** was synthesized according to our previous procedure.[14a] Related bis-hydroxy- and amine-functionalized analogues, **1b**,**c** respectively, were synthesized as shown in Scheme 3

The corresponding chloride-free complexes **2a**−**c** were prepared in situ upon treatment of **1a**−**c** with $AgBF_4$ (see the Supporting Information).

Starting from imidazole, bis-hydroxy-functionalized imidazolium salt **5** was prepared in 79% yield (Scheme 3). The ^{1}H NMR spectrum of **5** confirmed its symmetrical character and showed characteristic resonances corresponding to the

Scheme 3. (Top) Synthesis of Complexes 1b,c and (Bottom) Structures of NHC−Ir(III) Complexes 1a−c



imidazolium ring at δ 8.96 (1 H) and 7.65 (2 H) ppm and resonances corresponding to the two alkyl chains on the nitrogen substituents at δ 5.10 (2 OH), 4.13 (4 H), and 1.10 (12 H) ppm. The two hydroxy proton signals at δ 5.10 ppm disappeared upon treatment with D_2O. Reaction of **5** with Ag_2O yielded a carbene silver complex (**5′**), which, upon transmetalation with $[Cp^*IrCl_2]_2$, gave complex **1b** in 57% isolated yield. Imidazolium salt **8** was prepared from imidazole by a four-step synthetic route involving an Fe(III)-mediated addition of sodium azide to alkene intermediate **6**.[34] The ^{1}H NMR spectrum of **8** also showed the characteristic resonances at δ 9.29 (1 H) and at 7.79 (2 H) ppm corresponding to the imidazolium ring and at δ 4.59 (2 H) and 1.48 (6 H) ppm due to the amino alkyl chain (see the Supporting Information for further details). The signals at δ 4.30 (2 H), 1.97 (2 H), 1.48 (2 H), and 0.99 (3 H) ppm confirmed the presence of the butyl chain. Complex **1c** was synthesized in 61% isolated yield from **8** using a synthetic procedure similar to that described for complex **1b**.

NHC−iridium(III) complexes **1b**,**c** (Scheme 3) were characterized by NMR spectroscopy and mass spectrometry. In addition, complex **1b** was characterized by single-crystal X-ray diffraction analysis. The ^{1}H NMR spectrum of **1b** in $CDCl_3$ features a symmetrical pattern. The carbene olefinic protons appear at δ 7.36 (s, 2 H) ppm and the methylene protons on the side chains as doublets at δ 5.17 (2 H) and 3.64 (2 H) ppm, with a geminal coupling constant of 13.3 Hz. The methyl substituents appear at δ 1.38 (6 H) and 1.31 (6 H) ppm, and the Cp* group appears at δ 1.50 ppm. The fact that the methylene protons appear with different chemical shifts with a large geminal coupling constant and that different chemical shifts are also observed for the methyl groups indicate that there is hydrogen bonding between the hydroxy groups and the chlorides. Single-crystal X-ray diffraction analysis of **1b** (Figure 1 left, and Figure S1 in the Supporting Information) confirmed the molecular structure of the complex.[35] In the solid state, intermolecular hydrogen bonds between the hydroxy groups and chloride ligands of neighboring complexes are formed.

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

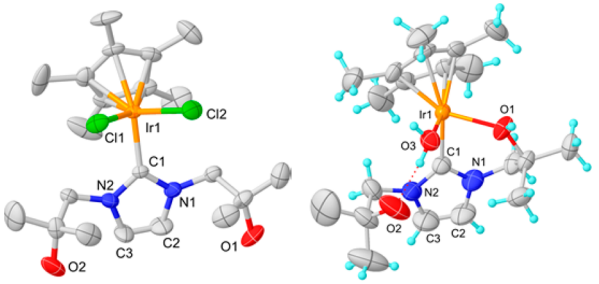


Figure 1. (left) Crystal structure of iridium complex **1b**[35] shown at 50% probability. Selected bond lengths (Å) and angles (deg): Ir(1)−C(1) 2.049(4), Ir(1)−Cl(1) 2.4317(11), Ir(1)−Cl(2) 2.4210(12), N(1)−C(1) 1.371(5), N(2)−C(1) 1.369(5); C(1)−Ir(1)−Cl(1) 94.41(11), C(1)−Ir(1)−Cl(2) 93.68(12), Cl(1)−Ir(1)−Cl(2) 83.22(5). Intermolecular hydrogen bonds between the hydroxy functionalities and the chloride ligands are observed: O(1) and Cl(1) 3.249 Å and O(2) and Cl(2) 3.220 Å. Hydrogen atoms are not shown for clarity. (right) Crystal structure of iridium complex **2b**[37] shown at 50% probability. Selected bond lengths (Å) and angles (deg): Ir(1)−C(1) 2.037(6), Ir(1)−O(1) 2.182(4), Ir(1)−O(3) 2.151(4), N(1)−C(1) 1.339(9), N(2)−C(1) 1.365(8); C(1)−Ir(1)−O(1) 85.2(2), C(1)−Ir(1)−O(3) 90.7(2), O(1)−Ir(1)−O(3) 81.31(2). A hydrogen bond (2.57 Å) between a labile water ligand (O(3)) and the nontethered hydroxy functionality (O(2)) is shown.

In contrast to complex **1b**, amine complex **1c** was obtained as a cyclic structure with the nitrogen bonded to the iridium, leaving chloride as a counteranion. The ^{1}H NMR spectrum agrees well with the structure of a cyclic cationic complex, which is expected as a result of the higher coordination ability of the amine group. The multiplicity observed for the NCH_2 protons in the butyl chain, at δ 4.29 ppm as a ddd (1 H) and δ 3.88 ppm as a ddd (1 H), agreed with previous observations for a related cyclic complex[14] and confirmed the cyclic structure of complex **1c**, in which the nitrogen atom is directly attached to the iridium center (Scheme 3). Additionally, the NH_2 protons are observed as two distinct doublets at δ 6.00 and 3.31 ppm, indicating a possible hydrogen bond between one of them and a chloride. Crystals suitable for X-ray analysis of **1c** were not obtained. However, the crystal structure of a related amine-functionalized NHC−Ir(III) complex[36] further supports the cationic cyclic structure proposed here for **1c**.

Following our previous report on the preparation of bis-cationic complex **2a**,[14a] the analogous complexes **2b,c** (Figure 2) were obtained upon treatment of **1b,c**, respectively, with $AgBF_4$ in CH_2Cl_2 (see the Supporting Information).

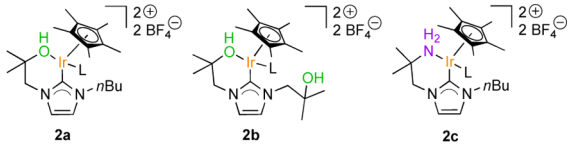


Figure 2. Bis-cationic NHC−Ir(III) complexes **2a−c**. L is a neutral ligand.

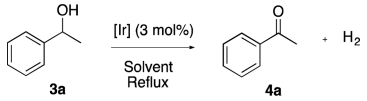
The synthesis and characterization of **2a** was reported in our previous work.[14] Complexes **2b,c** were characterized by ^{1}H NMR spectroscopy and also by single-crystal X-ray diffraction analysis in the case of **2b**. The variable-temperature (VT) ^{1}H NMR spectrum of **2b** in acetone-d_6 indicates a dynamic equilibrium where cyclic structures are formed through an alternative coordination of the hydroxy moieties to the iridium center (see Figure S2 in the Supporting Information). At −25 °C, this coordination swap is stopped, and the imidazole ring resonances move from a broad singlet (2 H) at δ 7.69 ppm to two doublets of 1 H each with a coupling constant of 1.8 Hz, at δ 7.76 and 7.64 ppm. The methylene protons become well-defined at −25 °C as two sets of two doublets: δ 4.69 and 4.27 (1 H, J = 14.2 Hz) and δ 4.45 and 3.94 (1 H, J = 14.9 Hz) ppm, and all four methyl groups on the tethers resonate at different chemical shifts at δ 1.61, 1.49, 1.44, and 0.94 ppm (3 H each). Therefore, VT NMR experiments clearly show that both OH-functionalized N wingtips on the NHC can coordinate to Ir. In contrast to **1b**, the hydroxy group in **2b** is coordinated to the iridium center both in $CDCl_3$ solution and in the solid state (Figure 1, right, and Figure S3 in the Supporting Information).[37] Single-crystal X-ray analysis of **2b** shows an intramolecular hydrogen bond between a labile water ligand and the hydroxy functionality that is not tethered to the iridium center.

The ^{1}H NMR spectrum of bis-cationic amine-functionalized complex **2c** was rather more similar to that of **1c**, except for a substantial shift from δ 6.00 to 4.33 ppm of one of the resonances corresponding to the NH_2 protons: in **1c** there is an interaction between one of these protons and the chloride, which is absent in **2c**.

For catalytic tests, chloride-free cationic complexes **2a−c** were prepared by addition of $AgBF_4$ to the corresponding chloride complexes **1a−c** in CH_2Cl_2. AgCl was removed by filtration, and the solvent was evaporated. The complexes thus prepared were used without further purification.

Catalytic Activity. The catalytic activity of **1a−c** and of **2a−c** in the acceptorless dehydrogenation (Scheme 2) of 1-phenylethanol (**3a**) was then evaluated (Table 1). In addition,

Table 1. Catalytic Activity of Cp*Ir(NHC) Complexes 1a−d and 2a−c[a]



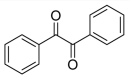
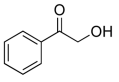
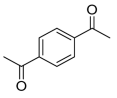
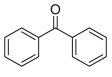
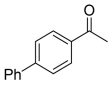
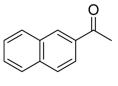
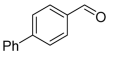
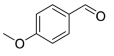
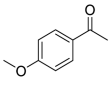
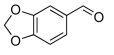
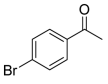
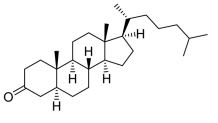
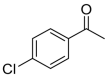
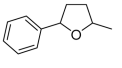
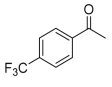
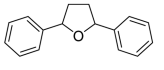
		yield (%)	
entry	[Ir]	in toluene[a]	in toluene/*t*-BuOH[b]
1	**1a**	51	17
2	**2a**	30	39
3	**1b**	39	18
4	**2b**	64	>99[c]
5	**1c**	5	3
6	**2c**	10	8
7	**1d**	24	21
8	**1d**/$AgBF_4$	9	81

[a]Conditions: 3 mol % [Ir], toluene, reflux, 15 h. [b]Conditions: 3 mol % [Ir], toluene/*t*-BuOH 3/1 (v/v), reflux, 15 h. [c]Full conversion after 12 h.

we also compared their activity to that of nonbifunctional NHC complex **1d**, Cp*Ir^{III}[NHC(nBu$_2$)].[38] The reactions were initially carried out in toluene, a solvent that gave excellent results in the alkylation of amines with alcohols catalyzed by **2a**.[14] The reactions were carried out at reflux in a Schlenk tube fitted with a condenser (oil bath temperature 130 °C, reaction time 15 h). Neutral complexes **1a−d** gave moderate to low conversions in toluene (Table 1, entries 1, 3, 5, and 7). Furthermore, the yields were very similar or even lower when

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

Table 2. Catalytic Acceptorless Alcohol Dehydrogenation of Alcohols and Diols by 2b[a]

Entry	Product	t (h)	Yield (%)[b]	Entry	Product	t (h)	Yield (%)[b]
1	 **4a**	15	>99[c]	13[d]	 **4m**	48	26[c]
2	 **4b**	24	>99[c]	14	 **4n**	15	76
3	 **4c**	15	79[c]	15[e]	 **4o**	24	71[c]
4	 **4d**	15	60	16	 **4p**	24	71[c]
5	 **4e**	24	72[c]	17	 **4q**	72	67[c]
6	 **4f**	15	80	18	 **4r**	72	26[c]
7	 **4g**	15	83	19	 **4s**	72	46[c]
8	 **4h**	15	71	20	 **4t**	24	28[c]
9	 **4i**	15	16[c]	21	 **4u**	72	47[c]
10	 **4j**	48	90	22	 **4v**	24	83[c]
11	 **4k**	48	84	23[f]	 **10a**	24	86 (62)[g]
12	 **4l**	48	83	24[f]	 **10b**	24	88 (63)[g]

[a]Conditions: alcohol (0.5 mmol), **2b** (0.015 mmol, 3 mol %), toluene (1.3 mL), *t*-BuOH (0.5 mL), reflux. [b]Isolated yields unless otherwise stated. [c]Yield determined by ^{1}H NMR spectroscopy, using 1,3,5-trimethoxybenzene as an internal standard. [d]From benzoin. [e]From the corresponding diol. [f]From the corresponding 1,4-diols. [g]Yields determined by ^{1}H NMR spectroscopy and isolated yields in parentheses.

the bis-cationic complexes were used (Table 1, entries 2, 4, 6, and 8). We next investigated the addition of a protic cosolvent to the reaction mixture. The addition of *t*-BuOH to the reactions catalyzed by complexes **1a−d** resulted in lower yields in comparison to those when toluene was used as the sole solvent (entries 1, 3, 5, and 7). An interesting result was observed, though, when the bis-cationic complexes were used in the solvent mixture toluene/*t*-BuOH; **2a,c** gave results similar to those obtained in just toluene (entries 2 and 6), but a substantial enhancement of the catalytic activity was observed

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

for **2b**, which gave a quantitative yield of **4a** after only 12 h (entry 4). This increase may be due to a proton-transfer or proton-relay effect, in which a protic species facilitates the dehydrogenation reaction (see the mechanistic investigation below).[3c,39] In a mechanism involving proton transfer steps, any chemical species that can temporarily carry protons will participate in the mechanism. Indeed, alcohol substrates **3a**−**v** can carry out that role. However, as the reaction proceeds the concentration of alcohol substrate diminishes, and so does the rate of the overall reaction. This is why a substantial increase of reaction rate is observed upon addition of *t*-BuOH, which guarantees a constant concentration of species that can shuttle protons (see Tables S1 and S2 and reaction kinetics on page S32 in the Supporting Information). Interestingly, a substantial improvement in the catalytic activity was also obtained for **1d**/$AgBF_4$ upon addition of *t*-BuOH (entry 8). Complex **1d** forms a bis-cationic complex upon reaction with $AgBF_4$, while bis-cationic **2a**,**b** easily evolve into mono-cationic complexes due to facile deprotonation of the alkoxide side arms under the reaction conditions.[14] This agrees with the higher activity boost for **1d**/$AgBF_4$ when *t*-BuOH is added to the reaction mixture in comparison to those for **2a**,**b** (entry 8 vs entries 2 and 4). Nevertheless, the best catalytic activity is obtained through combining the use of hemilabile bifunctional catalyst **2b** and a protic solvent such as *t*-BuOH (entry 4). Figure S4 in the Supporting Information shows the conversion based on evolved hydrogen volume in real time. In comparison to **1b**, the superior catalytic activity of **2b** may be related to the active participation of the second hydroxy moiety. The single-crystal X-ray analysis of **2b** (vide supra, Figure 1) shows that the second hydroxy group is intramolecularly hydrogen bound to a labile water molecule coordinated to iridium and thus placed in a privileged position near the metal active site. This clearly suggests that this second hydroxy-functionalized substituent on the NHC is not a mere spectator but can participate in the mechanism by hydrogen-bonding the alcohol substrates and positioning them in close proximity to the iridium center.

The use of H_2O instead of *t*-BuOH gave similar results (see Table S2 in the Supporting Information). However, *t*-BuOH was chosen over H_2O, as the reaction mixture was biphasic when the latter was used.

Substrate Scope. The scope of the acceptorless dehydrogenation of alcohols was studied using the best reaction conditions found (i.e., bis-cationic complex **2b** in a toluene/*t*-BuOH mixture, Table 1, entry 4). Benzylic *sec*-alcohols substituted with alkyl chains or aromatic rings, including naphthyl derivatives, were oxidized in good to excellent yields (Table 2, entries 1−8). A methoxy functionality at the para position was not well tolerated and gave a low yield of the expected ketone, together with symmetrical ethers and *p*-methoxystyrene (entry 9). Electron-deficient benzylic *sec*-alcohols were dehydrogenated in very good yields, although they required longer reaction times. For practical purposes, these substrates were allowed to react for 48 h (entries 10−12). It is worth mentioning that for halogenated substrates, entries 10 and 11, carbon−halogen bond cleavage did not occur. High yields were not obtained in the oxidation of benzoin (entry 13), possibly due to the electron-poor nature of this substrate. On the other hand, α-hydroxy-substituted alcohol **4n** efficiently underwent dehydrogenation (entry 14) selectively at the secondary alcohol. Double dehydrogenation of benzylic diol **4o** was achieved in good yield without increasing the catalyst loading (entry 15). Aliphatic *sec*-cyclic alcohol **4p** was dehydrogenated in 71% yield (entry 16). Even benzyl alcohol reacted to give benzaldehyde in 67% yield after 72 h (entry 17). Other primary benzylic alcohols gave moderate yields (entries 18−21). The bulky alcohol β-cholestanol gave the corresponding carbonyl derivative **4v** in very good yield (entry 22). When complex **2b** was tested on 1,4-diols **9a**,**b**, instead of an expected dehydrogenation reaction, these compounds were transformed into cyclic ethers **10a**,**b** (entries 23 and 24). Their ^{1}H NMR spectra indicated the presence of diastereomeric mixtures.[40,43]

Mechanistic Studies. The first step in the AAD reaction was investigated by subjecting enantiopure (*S*)-**3a** and (*S*)-**3a**-*d* to the reaction conditions (Table 3). This experiment can shed light onto the potential reversibility of the C−H bond-breaking step and can also give information about the rate-determining step (rds) of the reaction. When (*S*)-**3a** (>98% ee) was treated with **2b** in toluene/*t*-BuOH for 3 h under reflux, a 64% yield of acetophenone **4a** was obtained (Table 3, entry 1). Importantly, the remaining starting material **3a** had been racemized. This indicates that the C−H bond-breaking step is reversible, since the racemization process occurs through an oxidation/reduction sequence. Even when the reaction was carried out at significantly lower temperature (80 °C oil bath) for 3 h, the ee of the starting material decreased to 42% (entry 1). Similar results were obtained when toluene was used as the sole solvent, albeit, as expected, with lower yield (entry 2). When the same reaction was run with (*S*)-**3a**-*d*, a 54% yield of **4a** was obtained after 3 h. The remaining starting material had also been racemized, but in addition, **3a** had lost all deuterium content (entry 3). This result indicates that D/H exchange between (*S*)-**3a**-*d* and the solvent toluene occurs under the reaction conditions. Indeed, when toluene was replaced by toluene-d_8, the results were comparable in terms of yield and of ee, with the difference being that the deuterium content in the starting material remained intact (entry 4 vs 3).

When nondeuterated substrate **3a** was oxidized in toluene-d_8, the remaining unreacted starting material was completely deuterated, confirming a fast H/D exchange between the

Table 3. Racemization and H/D Scrambling in the AAD of (*S*)-3a-$d_{0,1}$ by 2b[a]

(*S*)-**3a** or (*S*)-**3a**-*d* **4a**

entry	**3a** (*t* = 0 h) ee (%)/D (%)	solvent	**3a** (*t* = 3 h) ee (%)/D (%)	**4a** (*t* = 3 h) (%)[b]
1	(*S*)-**3a**, >98/0	toluene/*t*-BuOH	0/0 (42/0)[c]	64 (21)[c]
2	(*S*)-**3a**, >98/0	toluene	0/0	59
3	(*S*)-**3a**-*d*, >98/>95	toluene	0/0	54
4	(*S*)-**3a**-*d*, >98/>95	toluene-d_8	0/>95	31
5	(*S*)-**3a**, >98/0	toluene-d_8	0/>95	38
6	(*S*)-**3a**-*d*, >98/>95	toluene-d_8/*t*-BuOH	0/95	56

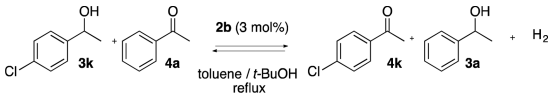
[a]Reaction conditions: alcohol (0.5 mmol), **2b** (0.015 mmol, 3 mol %), reflux, 24 h. [b]Yield determined by ^{1}H NMR spectroscopy, using 1,3,5-trimethoxybenzene as an internal standard. Percent deuterium was determined by ^{1}H NMR spectroscopy, and ee was determined by chiral GC. [c]In parentheses are given data for reaction carried out at 80 °C oil bath temperature.

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

substrates and the solvent (entry 5). The possible involvement of *t*-BuOH in these H/D exchange processes was also ruled out, since the deuterium content of (*S*)-**3a**-*d* did not change when the AAD was carried out in toluene-d_8 in the presence of nondeuterated *t*-BuOH (entry 6). This last experiment also confirms that the proton (O−*H*) and the hydrogen (C−*H*) keep their identities during the reaction.

Further support for the reversibility of the C−H bond-breaking step was obtained by carrying out the AAD of **3k** in the presence of acetophenone **4a** (**3k**/**4a** = 3/1) (Table 4). In this experiment, two competitive transformations can occur simultaneously: transfer hydrogenation, producing alcohol **3a** and ketone **4k**, as well as the expected AAD of both **3k** and **3a** to give **4k** and **4a**, respectively. Table 4 shows the composition of the reaction mixture at t = 0, 1, and 3 h. Alcohol **3a** could be formed by transfer hydrogenation with **3k**, and this would confirm the reversibility of the C−H breaking step in the catalytic cycle. After 1 h, the reaction mixture contained 14% of **3a**, and after 3 h 18% of **3a** was found. Note that alcohol **3a** can also undergo AAD to give **4a**. The formation of **3a** could also be accounted for through a hydrogenation reaction (i.e., reduction of **4a** by hydrogenation with the H_2 produced in the AAD reaction). This possibility was ruled out by studying the reverse overall reaction: i.e., hydrogenation of acetophenone **4a** catalyzed by **2b**. The reaction worked well in toluene/*t*-BuOH, but only when 10 atm of H_2 was used at 80 °C, and gave a 70% yield of **3**. Since a rather high pressure of H_2 was needed, it can be concluded that the reverse hydrogenation reaction is thermodynamically disfavored under the AAD reaction conditions. These results therefore confirm that formation of **3a** in the crossover experiment (Table 4) is due to a transfer-hydrogenation process. This further confirms the reversibility of the first oxidation step in the AAD.

Table 4. Crossover Experiment: Reaction of Alcohol 3k in the Presence of Ketone 4a[a]



entry	t (h)	**3k** (%)	**4a** (%)	**4k** (%)	**3a** (%)
1	0	75	25		
2	1	50	11	29	14
3	3	26	7	47	18

[a]Yield determined by ^{1}H NMR spectroscopy, using 1,3,5-trimethoxybenzene as an internal standard.

Kinetic investigations were carried out by monitoring the reactions by ^{1}H NMR spectroscopy. The reaction rates were lower when the reactions were run in NMR tubes than when the reflux-condenser setup described above for the substrate-scope investigation (Table 2) was used. This is due to a less efficient release of pressure. Due to H/D exchange with the solvent toluene, the magnitude of the kinetic isotope effect (KIE) under noncompetition conditions was estimated by comparing the initial rates of the AAD of **3a** in nondeuterated toluene to that of **3a**-*d* in toluene-d_8. Under these conditions, only H/H or D/D exchange between substrates and solvent occurs in each experiment, ensuring a constant hydrogen or deuterium content in the starting alcohols. A KIE of 2.0 ± 0.1 was obtained (Figure S6 in the Supporting Information).

The Hammett plot under noncompetition conditions is shown in Figure 3. A slight negative slope was obtained, with a rather small absolute value of ρ of only 0.26.[41]

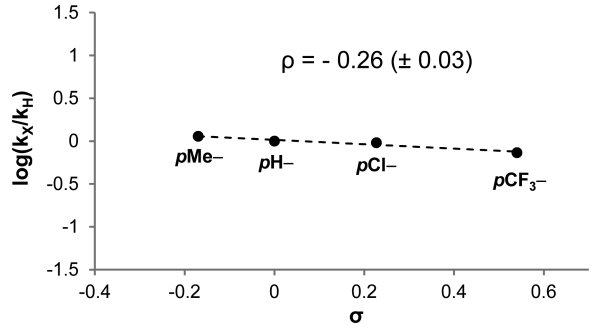


Figure 3. Hammett plot constructed from the relative rates obtained from noncompetition experiments with para-functionalized 1-phenylethanol derivatives **3a**,**e**,**k**,**l** ($y = -0.26x$ (±0.03) + 0.01 (±0.01), R^2 = 0.98).

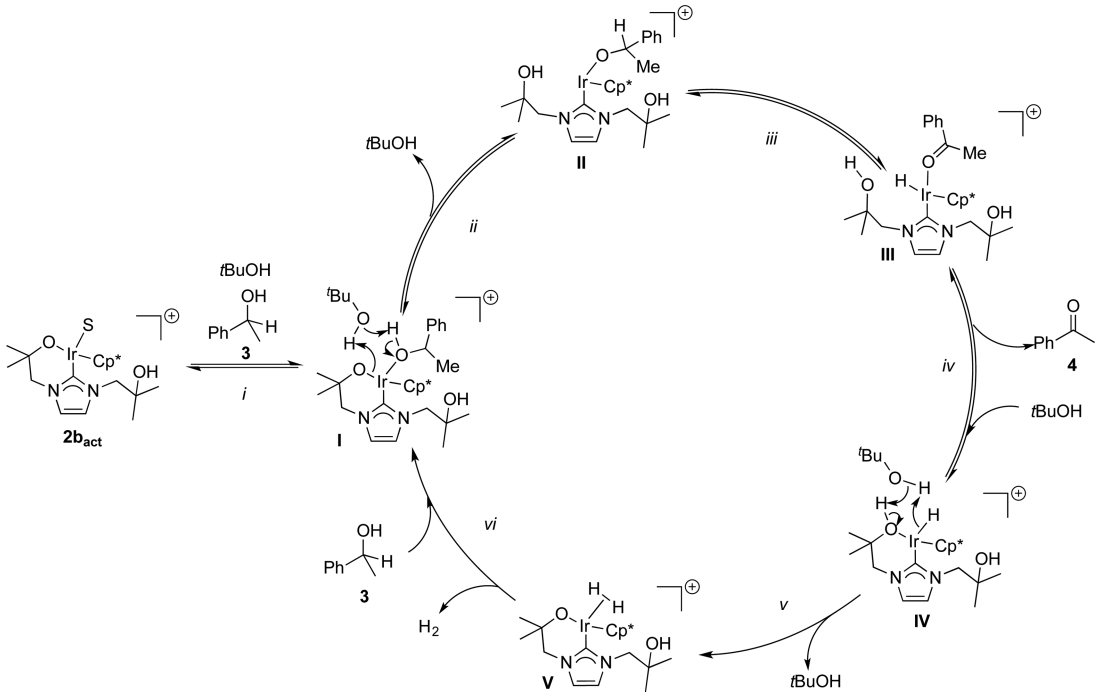
Regarding the effect of *t*-BuOH on the rate of the reaction, it was observed that it increases substantially when small amounts of this cosolvent were added, until ca. 9 mol %. A higher concentration of *t*-BuOH did not have a substantially greater effect on the rate of the reaction (Figure S5 in the Supporting Information).

Mechanistic Discussions. A mechanistic proposal for the AAD reaction based on the mechanistic investigations is presented in Scheme 4. The active catalytic species is formed upon deprotonation of the hydroxy group in one of the pendant arms of the NHC. Since the pK_a of this hydroxy group should be significantly lowered upon coordination to the iridium center,[14] *t*-BuOH or the substrate alcohol are sufficiently basic to carry out this deprotonation activation step. This is followed by coordination of the alcohol substrate **3a** to iridium to give intermediate **I** (step *i*). Deprotonation of the coordinated substrate through a proton transfer or proton relay mechanism involving *t*-BuOH gives alkoxide complex **II** (step *ii*). *β*-Hydride elimination from coordinatively unsaturated intermediate **II** results in alcohol oxidation with concomitant formation of an iridium hydride species (intermediate **III**, step *iii*). This step is reversible, as demonstrated in the racemization and transfer-hydrogenation experiments (vide supra, Tables 3 and 4, respectively). Recoordination of the hydroxy group of one of the side arms facilitates dissociation of the ketone product **4a** (step *iv*). To close the cycle, a *t*BuOH-assisted proton transfer facilitates the formation of molecular dihydrogen and the regeneration of alcohol complex **I**.

The small magnitude of the KIE (2.0 ± 0.1) and the small influence of the electronic properties of the substrates on the reaction rate (vide supra, ρ = −0.26, Figure 3) seem to rule out the possibility that the C−H bond-breaking step is the rds. Instead, all the data suggest that the rds of the catalytic cycle involves the step where the Ir−H bond is broken.[42] Since the rate is not completely independent of the electronic properties of the alcohol substrates (vide supra, Figure 3 and Table 2), the resting state of the catalytic cycle is probably intermediate **II** or intermediate **III**, both of which contain the (modified) reaction substrate. However, the negative slope of the Hammett experiment, which indicates that electronic density is lost, suggests that the rds corresponds to the process of passing from

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

Scheme 4. Proposed Catalytic Cycle for Solvent-Mediated Ligand-Assisted AAD Catalyzed by 2b



resting state **II** over the highest transition state **TSIV-V**, toward the formation of dihydrogen intermediate **V**.

The cyclization reaction of diols **9a,b** does not involve an overall dehydrogenation process. The mechanism may involve iridium-catalyzed hydrogen transfer processes. An alternative and straightforward mechanism would be an acid-mediated pathway where a proton or the iridium complex would act as an acid catalyst. The mechanism is currently under investigation and will be communicated in due course.

CONCLUSIONS

We have given a comparative analysis of two modes of metal−ligand cooperation in the acceptorless dehydrogenation of alcohols. A family of bifunctional amine-functionalized and hydroxy-functionalized Cp*Ir(NHC) complexes has been investigated, and their activities have been compared to that of a nonbifunctional Cp*Ir(NHC) complex. The screening clearly showed the benefits of including a hemilabile alcohol/alkoxide moiety in the catalyst structure, rather than an amine/amide functionality or an spectator ligand. The best results were obtained with catalyst **2b**, which has two hydroxy side chains on its NHC ligand. The activity is also dependent on the reaction conditions and in particular on the solvent system used. The presence of protic solvents enhanced the catalytic activity of complexes of **2b**, as these solvents facilitate proton-transfer steps between the catalyst and the substrates or products, thus improving the outcome of the AAD reaction through a proton transfer or proton-relay effect.

Bis-cationic complex **2b** showed a wide scope in the AAD of numerous alcohols. A catalytic or stoichiometric base was not needed. Although both secondary and primary alcohols could be oxidized, catalyst **2b** showed higher activity toward the former, allowing the chemoselective oxidation of secondary alcohols in substrates containing both types of alcohol functionalities.

Mechanistic investigations showed that the rds of the catalytic cycle involves breaking the Ir−H bond and that the electronic properties of the substrates have a rather small influence on the reaction rate. This explains the broad substrate scope of the AAD reaction catalyzed by **2b**.

The superior activity of the alcohol-/alkoxide-functionalized catalyst (**2b**) in comparison with the related amine-/amide-functionalized complex **2c** is somewhat surprising. Bifunctional catalysts bearing an amine/amide group have previously been shown to have substantially higher activity in redox reactions involving alcohol substrates in comparison to those where the bifunctionality of the catalyst relies on an alcohol/alkoxide moiety. With the results described in this paper, we have shown that significantly better performance is obtained as the result of an "OH effect" in the AAD mediated by Ir(III)−NHC complexes.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.7b00220.

Experimental details, ^{1}H NMR and ^{13}C NMR spectra, kinetic data, and crystallographic data (PDF)

Accession Codes

CCDC 1509620 and 1531608−1531609 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

AUTHOR INFORMATION

Corresponding Author

*E-mail for B.M.-M.: belen.martin.matute@su.se.

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

ORCID

Greco González Miera: 0000-0002-2856-5295
Belén Martín-Matute: 0000-0002-7898-317X

Author Contributions

†G.G.M. and E.M.-C. contributed equally.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This project was supported by the Swedish Research Council (VR) and the Knut and Alice Wallenberg Foundation. We also thank the Swedish Governmental Agency for Innovation Systems (VINNOVA) for a VINNMER grant to B.M.-M. E.M.-C. thanks the Wenner-Gren foundation for a postdoctoral scholarship. Prof. Per-Ola Norrby is gratefully acknowledged for fruitful mechanistic discussions, and. Dr A. Bartoszewicz and Dr R. Marcos are thanked for discussions.

■ REFERENCES

(1) (a) Khusnutdinova, J. R.; Milstein, D. *Angew. Chem., Int. Ed.* **2015**, *54*, 12236−12273. (b) Milstein, D. *Philos. Trans. R. Soc., A* **2015**, *373*, 20140189. (c) Trincado, M.; Grützmacher, H. Cooperating Ligands in Catalysis. In *Cooperative Catalysis: Designing Efficient Catalysts for Synthesis*; Peters, R., Ed.; Wiley-VCH: Weinheim, Germany, 2015. DOI: 10.1002/9783527681020.ch3. (d) Li, H.; Zheng, B.; Huang, K.-W. *Coord. Chem. Rev.* **2015**, *293*−*294*, 116−138.

(2) Zhao, B.; Han, Z.; Ding, K. *Angew. Chem., Int. Ed.* **2013**, *52*, 4744−4788.

(3) (a) Samec, J. S. M; Bäckvall, J.-E.; Andersson, P. G.; Brandt, P. *Chem. Soc. Rev.* **2006**, *35*, 237−248. (b) Muñiz, K. *Angew. Chem., Int. Ed.* **2005**, *44*, 6622−6627. (c) Ito, M.; Ikariya, T. *Chem. Commun.* **2007**, *48*, 5134−5142.

(4) Musa, S.; Shaposhnikov, I.; Cohen, S.; Gelman, D. *Angew. Chem., Int. Ed.* **2011**, *50*, 3533−3537.

(5) Moore, C. M.; Bark, B.; Szymczak, N. K. *ACS Catal.* **2016**, *6*, 1981−1990.

(6) (a) Ohkuma, T.; Ooka, H.; Hashiguchi, S.; Ikariya, T.; Noyori, R. *J. Am. Chem. Soc.* **1995**, *117*, 2675−2676. (b) Ohkuma, T.; Ooka, H.; Hashiguchi, S.; Ikariya, T.; Noyori, R. *J. Am. Chem. Soc.* **1995**, *117*, 10417−10418. (c) Hashiguchi, S.; Fuji, A.; Takehara, J.; Ikariya, T.; Noyori, R. *J. Am. Chem. Soc.* **1995**, *117*, 7562−7563.

(7) (a) Noyori, R.; Hashiguchi, S. *Acc. Chem. Res.* **1997**, *30*, 97−102. (b) Noyori, R.; Okhuma, T. *Angew. Chem., Int. Ed.* **2001**, *40*, 40−73. (c) Noyori, R.; Koizumi, M.; Ishii, D.; Ohkuma, T. *Pure Appl. Chem.* **2001**, *73*, 227−232. (d) Noyori, R.; Kitamura, M.; Ohkuma, T. *Proc. Natl. Acad. Sci. U. S. A.* **2004**, *101*, 5356−5362.

(8) (a) Ikariya, T.; Blacker, A. J. *Acc. Chem. Res.* **2007**, *40*, 1300−1308. (b) Ikariya, T.; Gridnev, I. D. *Top. Catal.* **2010**, *53*, 894−901. (c) Ikariya, T. *Bull. Chem. Soc. Jpn.* **2011**, *84*, 1−16.

(9) (a) Dub, P. A.; Ikariya, T. *ACS Catal.* **2012**, *2*, 1718−1741. (b) Li, H.; Hall, M. B. *ACS Catal.* **2015**, *5*, 1895−1913. (c) Eisenstein, O.; Crabtree, R. H. *New J. Chem.* **2013**, *37*, 21−27. (d) Sues, P. E.; Demmans, K. Z.; Morris, R. H. *Dalton Trans.* **2014**, *43*, 7650−7667. (e) Morris, R. H. *Acc. Chem. Res.* **2015**, *48*, 1494−1502. (f) Berben, L. A. *Chem. - Eur. J.* **2015**, *21*, 2734−2742. (g) Grützmacher, H. *Angew. Chem., Int. Ed.* **2008**, *47*, 1814−1818.

(10) Fujita, K.-i.; Tanino, N.; Yamaguchi, R. *Org. Lett.* **2007**, *9*, 109−111.

(11) Saha, B.; Rahaman, S. M. W.; Daw, P.; Sengupta, G.; Bera, J. K. *Chem. - Eur. J.* **2014**, *20*, 6542−6551.

(12) (a) Musa, S.; Filippov, O. A.; Belkova, N. V.; Shubina, E. S.; Silantyev, G. A.; Ackermann, L.; Gelman, D. *Chem. - Eur. J.* **2013**, *19*, 16906−16909. (b) Musa, S.; Fronton, S.; Vaccaro, L.; Gelman, D. *Organometallics* **2013**, *32*, 3069−3073. (c) Silantyev, G. A.; Filippov, O. A.; Musa, S.; Gelman, D.; Belkova, N. V.; Weisz, K.; Epstein, L. M.; Shubina, E. S. *Organometallics* **2014**, *33*, 5964−5973. (d) Musa, S.; Ghosh, A.; Vaccaro, L.; Ackermann, L.; Gelman, D. *Adv. Synth. Catal.* **2015**, *357*, 2351−2357.

(13) Chakraborty, S.; Piszel, P. E.; Brennessel, W. W.; Jones, W. D. *Organometallics* **2015**, *34*, 5203−5206.

(14) (a) Bartoszewicz, A.; Marcos, R.; Sahoo, S.; Inge, A. K.; Zou, X.; Martín-Matute, B. *Chem. - Eur. J.* **2012**, *18*, 14510−14519. (b) Bartoszewicz, A.; González Miera, G.; Marcos, R.; Norrby, P.-O.; Martín-Matute, B. *ACS Catal.* **2015**, *5*, 3704−3716.

(15) Chu, W.-Y.; Zhou, X.; Rauchfuss, T. B. *Organometallics* **2015**, *34*, 1619−1626.

(16) Geri, J. B.; Szymczak, N. K. *J. Am. Chem. Soc.* **2015**, *137*, 12808−12814.

(17) Nakano, R.; Nozaki, K. *J. Am. Chem. Soc.* **2015**, *137*, 10934−10937.

(18) (a) Kanai, M. In *Organic Chemistry−Breakthroughs and Perspectives*; Ding, K., Dai, L. X., Eds.; Wiley-VCH: New York, 2012; Chapter 11, p 385. (b) Askevold, B.; Roesky, H. W.; Schneider, S. *ChemCatChem* **2012**, *4*, 307−320.

(19) Peris, E. *Chem. Rev.* **2017**, DOI: 10.1021/acs.chemrev.6b00695.

(20) Carson, F.; Martínez-Castro, E.; Marcos, R.; González Miera, G.; Jansson, K.; Zou, X.; Martín-Matute, B. *Chem. Commun.* **2015**, *51*, 10864−10867.

(21) (a) Gunanathan, C.; Milstein, D. *Science* **2013**, *341*, 1229712. (b) Gunanathan, C.; Milstein, D. *Chem. Rev.* **2014**, *114*, 12024−12087. (c) Dobereiner, G. E.; Crabtree, R. H. *Chem. Rev.* **2010**, *110*, 681−703.

(22) (a) Jing, Y.; Chen, X.; Yang, X. *Organometallics* **2015**, *34*, 5716. (b) Hou, C.; Zhang, Z.; Zhao, C.; Ke, Z. *Inorg. Chem.* **2016**, *55*, 6539−3551.

(23) (a) Alberico, E.; Sponholz, P.; Cordes, C.; Nielsen, M.; Drexler, H.-J.; Baumann, W.; Junge, H.; Beller, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 14162−14166. (b) Fujita, K.-i.; Kawahara, R.; Aikawa, T.; Yamaguchi, R. *Angew. Chem., Int. Ed.* **2015**, *54*, 9057−9060. (c) *Hydrogen as a future energy carrier*; Züttel, A., Borgschulte, A., Schlapbach, L., Eds.; Wiley-VCH: Weinheim, Germany, 2008; DOI: 10.1002/9783527622894.

(24) (a) Crabtree, R. H. *Chem. Rev.* **2017**, DOI: 10.1021/acs.chemrev.6b00556. (b) Kaufhold, S.; Petermann, L.; Staehle, R.; Rau, S. *Coord. Chem. Rev.* **2015**, *304-305*, 73−87. (c) Johnson, T. C.; Morris, D. J.; Wills, M. *Chem. Soc. Rev.* **2010**, *39*, 81−88.

(25) (a) Delgado-Rebollo, M.; Canseco-Gonzalez, D.; Hollering, M.; Mueller-Bunz, H.; Albrecht, M. *Dalton Trans.* **2014**, *43*, 4462−4473. (b) Friedrich, A.; Schneider, S. *ChemCatChem* **2009**, *1*, 72−73. (c) Tseng, K.-N. T.; Kampf, J. W.; Szymczak, N. K. *Organometallics* **2013**, *32*, 2046−2049. (d) Tseng, K.-N. T.; Kampf, J. W.; Szymczak, N. K. *ACS Catal.* **2015**, *5*, 5468−5485. (e) Nielsen, M.; Kammer, A.; Cozzula, D.; Junge, H.; Gladiali, S.; Beller, M. *Angew. Chem., Int. Ed.* **2011**, *50*, 9593−9597. (f) Dutta, I.; Sarbajna, A.; Pandey, P.; Rahaman, S. M. W.; Singh, K.; Bera, J. K. *Organometallics* **2016**, *35*, 1505−1513.

(26) (a) Li, H.; Lu, G.; Jiang, J.; Huang, F.; Wang, Z.-X. *Organometallics* **2011**, *30*, 2349−2363. (b) Zeng, G.; Sakaki, S.; Fujita, K.-i.; Sano, H.; Yamaguchi, R. *ACS Catal.* **2014**, *4*, 1010−1020. (c) Gülcemal, S.; Gülcemal, D.; Whitehead, G. F. S.; Xiao, J. *Chem. - Eur. J.* **2016**, *22*, 10513−10522. (d) Valencia, M.; Müller-Bunz, H.; Gossage, R. A.; Albrecht, M. *Chem. Commun.* **2016**, *52*, 3344−3347. (e) Jiménez, M. V.; Fernández-Tornos, J.; Modrego, F. J.; Pérez-Torrente, J. J.; Oro, L. A. *Chem. - Eur. J.* **2015**, *21*, 17877−17889. (f) Ngo, A. H.; Adams, M. J.; Do, L. H. *Organometallics* **2014**, *33*, 6742−6745.

(27) (a) Maire, P.; Büttner, T.; Breher, F.; Le Floch, P.; Grützmacher, H. *Angew. Chem., Int. Ed.* **2005**, *44*, 6318−6323. (b) Wang, X.; Wang, C.; Liu, Y.; Xiao, J. *Green Chem.* **2016**, *18*, 4605−4610.

(28) (a) Bertoli, M.; Choualeb, A.; Lough, A. J.; Moore, B.; Spasyuk, D.; Gusev, D. G. *Organometallics* **2011**, *30*, 3479−3482. (b) Bertoli, M.; Choualeb, A.; Gusev, D. G.; Lough, A. J.; Major, Q.; Moore, B. *Dalton Trans.* **2011**, *40*, 8941−8949.

(29) (a) Song, H.; Kang, B.; Hong, S. H. *ACS Catal.* **2014**, *4*, 2889−2895. (b) Zell, T.; Milstein, D. *Acc. Chem. Res.* **2015**, *48*, 1979−1994. (c) Chakraborty, S.; Lagaditis, P. O.; Förster, M.; Bielinski, E. A.;

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX

Hazari, N.; Holthausen, M. C.; Jones, W. D.; Schneider, S. *ACS Catal.* **2014**, *4*, 3994−4003.
(30) (a) Zhang, G.; Hanson, S. K. *Org. Lett.* **2013**, *15*, 650−653. (b) Zhang, G.; Vasudevan, K. V.; Scott, B. L.; Hanson, S. K. *J. Am. Chem. Soc.* **2013**, *135*, 8668−8681. (c) West, J. G.; Huang, D.; Sorensen, E. J. *Nat. Commun.* **2015**, *6*, 10093.
(31) Tan, D.-W.; Li, H.-X.; Zhang, M.-J.; Yao, J.-L.; Lang, J.-P. *ChemCatChem* **2017**, *9*, 1113−1118.
(32) Tilgner, D.; Friedrich, M.; Hermannsdörfer, J.; Kempe, R. *ChemCatChem* **2015**, *7*, 3916−3922.
(33) Kim, W.-H.; Park, I. S.; Park, J. *Org. Lett.* **2006**, *8*, 2543−2545.
(34) Leggans, E. K. T.; Barker, T. J.; Duncan, K. K.; Boger, D. L. *Org. Lett.* **2012**, *14*, 1428−1431.
(35) CCDC 1531608 contains the supplementary crystallographic data for this structure. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.ac.uk/data_request/cif.
(36) CCDC 1509620 contains the supplementary crystallographic data for this structure. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.ac.uk/data_request/cif.
(37) CCDC 1531609 contains the supplementary crystallographic data for this structure. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.ac.uk/data_request/cif.
(38) Corberán, R.; Sanaú, M.; Peris, E. *J. Am. Chem. Soc.* **2006**, *128*, 3974−3979.
(39) (a) Matsunami, A.; Kayaki, Y.; Ikariya, T. *Chem. - Eur. J.* **2015**, *21*, 13513−13517. (b) Ito, M.; Hirakawa, M.; Murata, K.; Ikariya, T. *Organometallics* **2001**, *20*, 379−381. (c) O, W. W. N.; Lough, A. J.; Morris, R. H. *Organometallics* **2012**, *31*, 2152−2165. (d) O, W. W. N.; Lough, A. J.; Morris, R. H. *Organometallics* **2012**, *31*, 2137−2151. (e) Casey, C. P.; Johnson, J. B.; Singer, S. W.; Cui, Q. *J. Am. Chem. Soc.* **2005**, *127*, 3100−3109. (f) O, W. W. N.; Lough, A. J.; Morris, R. H. *Chem. Commun.* **2009**, *46*, 8240−8242. (g) Barnard, J. H.; Wang, C.; Berry, N. G.; Xiao, J. *Chem. Sci.* **2013**, *4*, 1234−1244. (h) Wang, W.-H.; Xu, S.; Manaka, Y.; Suna, Y.; Kambayashi, H.; Muckerman, J. T.; Fujita, E.; Himeda, Y. *ChemSusChem* **2014**, *7*, 1976−1983. (i) Onishi, N.; Xu, S.; Manaka, Y.; Suna, Y.; Wang, W.-H.; Muckerman, J. T.; Fujita, E.; Himeda, Y. *Inorg. Chem.* **2015**, *54*, 5114−5123.
(40) Selected recent articles: (a) Aricò, F.; Evaristo, S.; Tundo, P. *Green Chem.* **2015**, *17*, 1176−1185. (b) Aricò, F.; Tundo, P.; Maranzana, A.; Tonachini, G. *ChemSusChem* **2012**, *5*, 1578−1586. (c) Shibata, T.; Fujiwara, R.; Ueno, Y. *Synlett* **2005**, *1*, 152−154. (d) Zhou, H.; Song, J.; Meng, Q.; He, Z.; Jiang, Z.; Zhou, B.; Liu, H.; Han, B. *Green Chem.* **2016**, *18*, 220−225. (e) Jackson, M. A.; Appell, M.; Blackburn, J. A. *Ind. Eng. Chem. Res.* **2015**, *54*, 7059−7066. (f) Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Shirai, M. *Catal. Today* **2012**, *185*, 302−305. (g) Yamaguchi, A.; Hiyoshi, N.; Sato, O.; Shirai, M. *ACS Catal.* **2011**, *1*, 67−69. (h) Grochowski, M. R.; Yang, W.; Sen, A. *Chem. - Eur. J.* **2012**, *18*, 12363−12371.
(41) (a) Hammett, L. P. *J. Am. Chem. Soc.* **1937**, *59*, 96−103. (b) Ingold, C. K.; Shaw, F. R. *J. Chem. Soc.* **1927**, *0*, 2918−2926.
(42) (a) Simmons, E. M.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2012**, *51*, 3066−3072. (b) Gómez-Gallego, M.; Sierra, M. A. *Chem. Rev.* **2011**, *111*, 4857−4963.
(43) This series of experiments with **9a,b** was carried out in a pressure tube, rather than in a Schlenk tube and condenser system, since we anticipated that H_2 gas would not be produced and so a larger head space would not be needed.

DOI: 10.1021/acs.organomet.7b00220
Organometallics XXXX, XXX, XXX−XXX