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Umpolung of B–H Bonds by Metal–Ligand Cooperation with Cyclopentadienone Iridium Complexes

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Abstract: Contrastive that the conventional metal-ligand cooperative cleavage of a B-H bond provides a B cation on the ligand and an H anion on the metal, herein we report the first umpolung of B-H bonds by novel cyclopentadienone iridium complexes. For HBpin (= 4,4,5,5tetramethyl-1,3,2-dioxaborolane) and HBdan (= 1.8naphthalenediaminatoborane), the B-H bonds were cleaved into a B anion on the metal and an H cation on the phenolic oxygen in the ligand. The mechanistic investigation by DFT calculations revealed that the alkoxycarbonyl-substituted cyclopentadienone ligand facilitated the deprotonation from Ir-H after oxidative addition of the B-H bond to give the umpolung product. The generated boryliridium complex was found to undergo borylation of allyl halide in the presence of base to show nucleophilic nature of the boron atom.

Umpolung, polarity inversion of bonds, is one of the most important processes in synthetic organic chemistry to form a new chemical bond which is highly difficult to access. As boron is more electropositive than hydrogen, B–H bonds are polarized into $B^{\delta+}$ and $H^{\delta-}$.[1] Owing to the hydridic nature of hydrogen in hydroboranes, the latter have long been used in organic syntheses, such as the reduction of carbonyl compounds, anti-Markovnikov hydroboration of unsaturated carbon–carbon bonds etc.[2,3] The electropositive nature of the boron atom, however, makes it difficult to use hydroborane as a boron nucleophiles[4,5] and thus plenteous chemistry has been brought up with diboron or silylborane as boryl anion equivalents.[6]

One way to activate B–H bonds by transition metal complexes is the oxidative addition, that is the homolytic cleavage of a B–H bond on the central metal to generate a B anion and an H anion. Alternatively, metal–ligand cooperative heterolytic cleavage has been attracting emerging attention in the last decade.[7–9] Figure 1 summarizes the representative reports for B–H bond cleavage by metal–ligand cooperation: (a) ruthenium thiolate by Ohki, Tatsumi, and Oestreich,[10] (b) *N*,O-chelated phosphoramidate by Schafer, Love, and Weller,[11] (c) palladium carbene by Iluc,[12] and (d) cyclopentadienone ruthenium dimer by Casey and Clark.[13] In all of these precedents, each B–H bond is cleaved into an H *anion* on the metal and a B *cation* on the electronegative atom of the ligand, which is inheriting the

polarization in the parent B–H bonds.[9] To the best of our knowledge, there is no report for the cleavage of a B–H bond with a metal–ligand bifunctional complex to give a B *anion* on the metal and an H *cation* on the ligand.[14]

Here in this study, we report the first umpolung cleavage of the B–H bond by cyclopentadienone iridium hydride complex (Figure 1e). The DFT studies revealed that the alkoxycarbonyl-substituted cyclopentadienone ligand specifically gave the umpolung product by facilitating deprotonation by the carbonyl oxygen on the ligand. The acidity of the hydrogen and nucleophilicity of the boron after the metal–ligand cooperative umpolung of B–H bonds were demonstrated in the reactions with base and allyl halides to afford allyl boronate as products.



Figure 1. Metal-ligand cooperative B-H bond cleavage.

The iridium(I) hydride complexes bearing phenyl-, ethyl-, or ethoxycarbonyl-substituted cyclopentadienone ligand (4a-4c) were synthesized in three or four steps from the corresponding ligands 1a-1c (Scheme 1). Iridium chloride complexes 2a-2c were prepared in a similar manner to the previous literature.[15] When the complexes 2a and 2c were placed under the H₂ atmosphere in tetrahydrofuran (THF), gradually the color of the solution changed from purple to yellow to form hydroxycyclopentadienyl iridium(III) chloride hydride complexes 3a and 3c, respectively (Scheme 1b). The complexes were then

treated with 0.5 equivalent of Ag₂O in the presence of acetonitrile to give the desired penta-coordinate cyclopentadienone iridium(I) hydride complexes **4a** and **4c**. Complex **4b** was directly synthesized from **2b** by the reaction with sodium formate via decarboxylative hydridation (Scheme 1c). The structures of complexes **4a**–**4c** were spectroscopically determined, and those of **4b** and **4c** were unambiguously determined by single-crystal Xray diffraction analysis (Figure 2a for complex **4c** and Figure S82 for complex **4b**).

The reactivities of these cyclopentadienone iridium(I) complexes (**4a–c**) with hydroboranes were examined and the results are summarized in scheme 2. The addition of 5 equivalents of HBpin (= 4,4,5,5-tetramethyl-1,3,2-dioxaborolane) to the solution of complex **4a** in benzene at room temperature led to the generation of boroxycyclopentadienyl iridium(III) dihydride complex **6a** as a major product observed in ¹H-NMR spectrum. On the other hand, when complex **4b** was allowed to react with 5 equivalents of HBpin, hydroxycyclopentadienyl boryliridium hydride complex **5b** was observed as a major product, along with **6b** as a minor product (**5b** 61%, **6b** 33%). The reaction of **4c** with HBpin provided exclusive formation of boryliridium complex **5c** (96% NMR yield, 55% isolated yield by silica-gel column chromatography, Scheme 2a).



Scheme 1. Structures of the cyclopentadienone ligands and synthesis of the cyclopentadienone iridium(I) hydride complexes 4a-4c.

The structure of complex 5c was determined by NMR spectroscopy and X-ray crystallography (Figure 2b). In the ¹H-NMR spectrum, a signal of O-H on the hydroxycyclopentadienyl ligand was observed as a singlet at δ 9.50 ppm and Ir–H at δ – 20.8 ppm with coupling with ³¹P (${}^{2}J_{HP}$ = 29.1 Hz). It is worth noting that there was no observable J coupling with ¹¹B, which indicates no significant interaction between the hydride and the boron atom exists in 5c. In ¹¹B-NMR spectrum, a broad signal, corresponding to Ir–Bpin, was observed at δ 27 ppm, which is consistent with the analogous boryliridium complex (Cp*Ir(PMe₃)(Bpin)H, δ 33 ppm).[16] Complex 5c was stable enough to show no significant structural change in benzene solution at room temperature for more than two days. Then the scope of hydroboranes was investigated (Scheme 2b). While HBdan (= 1.8naphthalenediaminatoborane) also afforded boryliridium(III) complex 5c-Bdan, the use of 9-BBN or HBhex (= 4,4,6-trimethyl-1,3,2-dioxaborinane) resulted in the formation of complexes 6c**9BBN** and **6c-Bhex** having an H atom on the metal and a B atom on the ligand with small amount of hydroxyCp iridium dihydride complex, presumably formed via hydrolysis of B–O bond in **6** (supporting information).



Scheme 2. Reactions of the cyclopentadienone-Ir complexes with hydroboranes.^a ^aTypical reaction conditions: complex **4**, hydroborane (5 equiv.), benzene, room temperature, 5 min. Yield calculated by ¹H-NMR spectroscopy using 1,3,5-trimethoxybenzene as an internal standard. ^bThe reaction time was five hours. ^{c1} equivalent of hydroborane was added.



Figure 2. X-ray structure of complex 4c and 5c (thermal ellipsoids are drawn with 50% probability. Hydrogens on carbon atoms are omitted for clarity.).

The selective formation of complex **5c** from complex **4c** was next rationalized by DFT calculations using model structure **4c'** and (ethylene glycol)borane (see Figure 3). All the calculations (geometry optimization, frequency and IRC calculations) were performed with rM06 function and def2-tzvp basis set with associated effective core potentials unless otherwise noted. The results are summarized in Figure 3, showing the free energies in all the intermediates and transition states in kcal/mol with respect to **4c'**.[17] The validity of the use of the simplified model structures was ensured by comparison of the key free energy values to those calculated with the real structures (Figure S87). First of all, **5c'** is calculated to be thermodynamically much less

stable than **6c**' by 20.3 kcal/mol (Figure 3a, compare **5c**' with **6c**'). Therefore, the formation of **5c** was kinetically controlled and not via isomerization from **6c**. Further theoretical calculation revealed

the reaction proceeds via the first coordination of B–H bond followed by oxidative addition of the B–H bond directly to the iridium center ($4c' \rightarrow Int-II$) and then



Figure 3. Computed energy profiles for the reaction of complex 4 with HBpin (simplified structures and (ethylene glycol)borane were used for calculations. Substituents are omitted from the structures on the figure for clarity). Gibbs free energy values calculated by rM06/def2-tzvp (red: reaction path for umpolung product 5, blue: reaction path for complex 6).

deprotonation by another iridium complex (TS_{II-III}(cis-H)). This nicely explains the observed umpolung of B-H bonds and the different selectivity dependency on the ligand substituents (i.e. 6a and 5c on Scheme 2). The first dissociative replacement of the coordinated acetonitrile in 4c' by a B-H bond (4c'→Int-I→TS_{I-II}) followed by almost barrierless oxidative addition of the B-H bond (see Figure S84, S85 for the energy scans along the reaction coordinate) takes place to give Int-II. There exist cis/trans isomers for Int-II where two hydrides occupy the trans (Int-II(trans)) or cis (Int-II(cis)) coordination sites to each other. Although Int-II(trans) is more stable than Int-II(cis) by 6.0 kcal/mol, Int-II(cis) was *kinetically* more accessible $(4c' \rightarrow Int-I \rightarrow TS_{I-II}(cis) \rightarrow Int-II(cis))$, 13.6 kcal/mol) than Int-II(trans) in trans geometry (4c'→Int-I-TSI-II(trans)-Int-II(trans), 18.3 kcal/mol) (see supporting information for further discussion, section V-VII). While migration of boron atom on Int-II from the iridium center to the ligand would give the normal product 6c' (highlighted in blue), that of hydrogen atom would conversely afford the umpolung product 5c' (highlighted in red). The deprotonation of the Ir-H on the kinetic intermediate, Int-II(cis) by another iridium complex (TS_{II-III}(cis-H)) could proceed with a reasonable ΔG^{\ddagger} value of 16.6 kcal/mol relative to 4c', while that of the deboration from Int-II(cis) was far higher in energy (TS_{II-III}(cis-B), 25.8 kcal/mol relative to 4c').[17] This strong preference of deprotonation to deboration from the cis

isomer would be because of the following two reasons. First, the two hydrides in Int-II(cis) can reductively eliminate to form metastable dihydrogen complex (Int-II(cis-H₂), 4.9 kcal/mol relative to Int-II(cis)) (red line). Therefore, the two hydrogens in TS_{II-III}(cis-H) have a character of coordinating dihydrogen, which can be more protic than the iridium hydride in the parent intermediate Int-II(cis). Second, the proton to be abstracted by the central carbonyl oxygen can have the additional interaction with the alkoxycarbonyl oxygen of the ligand. The boron atom, on the other hand, cannot be stabilized by any additional fifth coordination in TS_{II-III}(cis-B). This explanation is consistent with the fact that the transition state is much more significantly stabilized with the alkoxycarbonyl substituted ligand but less with the phenyl substituted ligand (vide infra). The generated ionic pair (Int-III) of anionic cyclopentadienone iridium(I) complex and cationic hydroxycyclopentadienyl iridium(V) complex underwent proton transfer from the Ir-H on the cationic part to the ligand on the anionic part with negligible activation energy to afford the umpolung product, complex 5c' (see Figure S86 for the free energy scans in this proton transfer process). Deprotonation from Int-II(trans) requires much higher activation energy (TSII-III(trans-H), 22.5 kcal/mol, relative to 4c'), compared to TS_{II-III}(cis-H) and thus the trans isomer rather prefers deboration via $TS_{II-III}(trans-$ B) (16.0 kcal/mol, relative to 4c') to give complex 6c'. It should be

noted that $TS_{II-III}(cis-H)$ is sufficiently stabilized, which resulted in the deprotonation from Int-II(cis) (Int-II(cis) $\rightarrow TS_{II-III}(cis-H) \rightarrow Int-III)$ [18] being more favorable than the isomerization of Int-II(cis) into the thermodynamically more stable intermediate Int-II(trans) (Int-II(cis) $\rightarrow TS_{I-II}(cis) \rightarrow Int-I \rightarrow TS_{I-II}(trans))$

followed by the deboration via TS_{II-III}(trans-B). This difference in the ΔG^{\ddagger} values eventually resulted in the exclusive progress of deprotonation of Ir-H from the kinetically favored cis isomer Int-II(cis). Other possibilities for the B-H bond cleavage via direct addition with or without mediator from Int-I, which is similar to the classical metal-ligand cooperative bond cleavage/formation of H-H and C-H bonds,[19,20] were located at high in energy, 30.3 kcal/mol or 53.5 kcal/mol relative to 4c' (Figure S88). In sharp contrast to the energy profile with 4c', when the phenylsubstituted cyclopentadienone iridium complex 4a' was employed, ΔG^{\ddagger} value of deprotonation transition state from the *cis* intermediate (TS_{II-III}(Ph-cis-H)) is higher to be inaccessible (Figure 3b, 28.0 kcal/mol relative to 4a'). Therefore, with phenylsubstituted complex, the easier deboration from the thermodynamically favored trans intermediate Int-II(Ph-trans) (TS_{II-III}(Ph-trans-B), 17.4 kcal/mol relative to 4a') is likely to proceed, which will give the normal product 6a'. This different reactivity of complex 4c' from 4a' towards the deprotonation from intermediates after the B-H bond oxidative addition (Int-II) could mainly originate from the presence (absence) of the additional carbonyl groups to stabilize the leaving proton (vide supra).

The observed opposite selectivity between **5c** and **6c** with HBpin, 9-BBN and HBhex (Scheme 2b) could also be reproduced by DFT calculations (see Figure S89, S90 in supporting information). When 9-BBN was employed as a hydroborane, the deprotonation from the *cis*-intermediate after the oxidative addition of B–H bond in 9-BBN was inaccessible, while the deboration from the *trans*-isomer with 9-BBN was more facilitated most probably because of the higher Lewis acidity of the boron atom of 9-BBN. And when HBhex is employed in calculations, the transition state for the coordination of HBhex to **Int-I** in cis manner, **TS**_{HI}(**Bhex-trans**), probably because Bhex has larger steric repulsion with the phosphine ligand than Bpin, which explains the exclusive deboration from the trans intermediate, **Int-II(Bhex-trans)**, to give the normal product **6c-Bhex** (Figure S90).

The protic nature of the hydrogen on the ligand and the nucleophilicity of the boron on the iridium center on complex 5c were next demonstrated in the reaction with base and allylic halides. When complex 5c was treated with sodium hydride, gradually H₂ bubbles appeared along with the formation of a new single species on ¹H-NMR spectrum. The formed complex was characterized to be an anionic cyclopentadienone boryliridium(I) complex 7c, indicating the OH proton is acidic enough to be deprotonated. (Scheme 3a and supporting information). The nucleophilicity of the boryl group on the iridium was demonstrated in the reaction of complex 7c with allyl halides (Scheme 3b). The reaction of complex 7c with allyl halides at room temperature for 15 hours afforded allyl-Bpin (X = I; 58%, X = Br; 42%), which indicates the nucleophilic nature of the boron center on the iridium. Since the reaction did not proceed with benzyl bromide or 3,3dimethylallyl bromide), the nucleophilic attack of the boryl group would take place at the γ -position via S_N2' pathway (see supporting information for further investigations with other substrates and catalytic reactions).

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Scheme 3. Synthesis and Reactivity of Complex 7c.

In conclusion, the umpolung of the B–H bonds in HBpin and HBdan into a boryl group on the metal and an H cation on the ligand was achieved by metal–ligand cooperation by the cyclopentadienone iridium complex **4c**. The mechanistic investigations supported the oxidative addition of B–H bond and following deprotonation by another iridium complex. The highly basic alkoxycarbonyl-substituted cyclopentadienone ligand dramatically lowered the activation energy of the deprotonation to enable the exclusive formation of the umpolung product **5c**. Possible application of this umpolung reaction of B–H bonds to nucleophilic borylation was demonstrated in the borylation of allyl halide with HBpin to afford allylboronate as a major product. Herereported metal–ligand cooperative umpolung of B–H bond will open up new strategies for preparation and transformation of organoboron compounds.

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Keywords: Umpolung • Metal–Ligand Cooperation • Cyclopentadienone • Iridium • Hydroborane

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- (18) The value is calculated by the way shown in ref.17 to be 12.7 kcal/mol, which is lower than that of the isomerization of Int-II(cis) into Int-II(trans) followed by the deboration (16.4 kcal/mol).
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Although the conventional heterolytic cleavage of a B–H bond provides a B cation on the ligand and an H anion on the metal, herein we report the first umpolung of B–H bonds by a novel cyclopentadienone iridium complexes. The B–H bond in HBpin was cleaved into a B *anion* on the metal and an H *cation* on the phenolic oxygen in the ligand.