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Communication

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Olefin Oxygenation by Water on an Iridium Center

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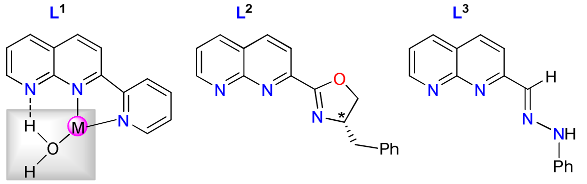
Supporting Information Placeholder

ABSTRACT: Oxygenation of 1,5-cyclooctadiene (COD) is achieved on an iridium center using water as a reagent. Hydrogen bonding interaction with an unbound nitrogen atom of the naphthyridine-based ligand architecture promotes nucleophilic attack of water to the metal-bound COD. Iridaoxetane and oxo-irida-allyl compounds are isolated, products which are normally accessed from reactions with H_2O_2 or O_2. DFT studies support a ligand-assisted water activation mechanism.

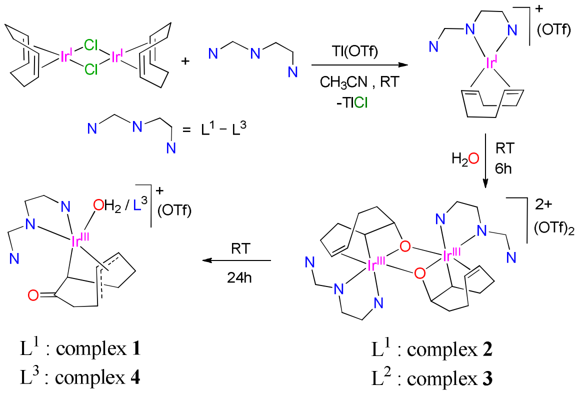
The use of water as substrate in metal-catalyzed organic transformations has been limited. A few examples are anti-Markovnikov hydration of alkynes,[1] nitrile hydration,[2] cyclic amines to lactams,[3] water-gas shift reaction[4] and aldehyde-water shift reaction.[5] Grotjahn *et al.* reported a variety of bifunctional metal catalysts for alkyne hydration, where pendant basic groups attached to the ligands serve as the internal base for water activation.[6] Photocatalytic water oxidation in presence of organometallic complexes is a fundamentally important reaction.[7] Milstein and coworkers demonstrated bifunctional water splitting by dearomatized [Ru–PNN] pincer complex and subsequent light induced formation of O_2 in a stoichiometric manner.[8] The water addition proceeds via initial metal coordination followed by proton migration to the cooperating ligand.[9] Thus, the metal-ligand interplay provides an alternate pathway for water activation that is kinetically more accessible than the direct oxidative addition of water to the metal.[10]

The water addition to a metal is associated with an entropic penalty.[11] Hydrogen bonding interaction in the secondary coordination sphere may compensate for this entropic loss. The 1,8-naphthyridine ligands L^1–L^3, shown in Scheme 1, offer prospect for simultaneous metal coordination and hydrogen bond interaction with the ligand architecture. Such interactions promote nucleophilic attack of water to a metal-bound substrate and thus favor hydration reactions.[2a] Water reactions have been largely carried out with Pd, Ru and Rh, but a parallel chemistry with iridium is not known. Herein we describe the first case of olefin oxygenation by water on an iridium center. A prolonged reaction (24 h) of Ir^I(COD) with L^1 in the presence of water affords a 5-oxo-6-irida(1,2,3)-allyl compound **1** (Scheme 2). While performing the same reaction for 6 h, a 2-iridaoxetane intermediate **2** is isolated as a dimer which readily rearranges to **1** in solution. Use of L^2 ligand with bulky benzyl substituent at the *ortho* position to the coordinating nitrogen in the oxazoline ring gives only the oxetane analogue **3** , whereas L^3 ligand bearing a flexible anilinyl group afforded an oxo-irida-allyl analog **4**, but the corresponding oxetane compound could not be isolated. Experiments with H_2O^{18} unambiguously establish that the source of oxygen in the oxygenated compounds is water and not adventitious oxygen. Density functional theory (DFT) calculations support a ligand assisted bifunctional water activation pathway as a superior alternative to oxidative addition.

Scheme 1. Naphthyridine based ligands employed in this work. Simultaneous metal coordination and H-bonding interaction of water with ligand scaffold is shown for L^1.



Scheme 2. Syntheses of 2-iridaoxetane dimers and 5-oxo-6-iridia(1,2,3)-allyl compounds in the water reactions.



Ir(I) complexes containing COD generally show limited reactivity with molecular O_2 and moisture. Removal of bridging chlorides in $[IrCl(COD)]_2$ by TlOTf in acetonitrile and subsequent treatment with L^1 afforded a stable complex $[Ir(COD)(L^1)](OTf)$ (Scheme 2).[12] Subsequent reaction with 10 fold excess of degassed, deionized H_2O at room temperature for 24 hours afforded the 5-oxo-6-irida(1,2,3)-allyl compound **1**. The molecular structure of **1**, depicted in Figure 1, shows η^1, η^3–coordination of COD. The C_5 carbon is oxidized to carbonyl with a C=O distance of 1.217(1) Å. The naphthyridine ligand chelates the metal and is disposed *trans* to the allyl unit (Ir–C = 2.145(8), 2.105(8) and 2.154(8) Å). The Ir–C(alkyl) distance is 2.056(7) Å. Coordination by a water molecule completes octahedral geometry around the metal.

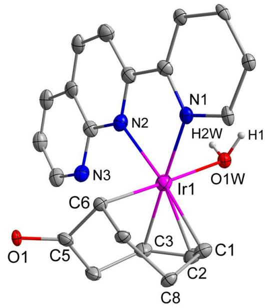


Figure 1. Molecular structure of the cationic unit $[Ir(C_8H_{10}O)(L^1)(H_2O)]$ in **1**.

The ^{1}H-NMR spectrum of **1** (Figure S4) in deuterated acetonitrile is broadly divided into three regions. Nine aromatic protons of the ligand appear in the range between δ = 7.77–9.69 ppm. Six methylene protons and one methyne proton of COD appear in the range of δ = 1.05–2.58 ppm, while three allylic protons show signals further upfield (δ = 4.64–5.40 ppm). Signal attributable to metal-coordinated water was not observed indicating that CD_3CN possibly displaces the water at the metal center. The ^{13}C-NMR showed a characteristic signal at δ = 220.5 ppm assigned to the carbonyl carbon. A strong band at 1666 cm^{-1} in the IR spectrum supports the presence of the carbonyl group. ESI–MS at *m*/*z* = 522.098 is attributed to $[M–H_2O–OTf]^+$ (Figure S9a).

With the intent to isolate a possible intermediate, the reaction was quenched after 6 h and an irida^{III}-oxetane dimer **2** was obtained. Another oxetane analog **3** was also isolated using L^2. Complex **2** has a crystallographically imposed inversion center and only half of the molecule appears in the asymmetric unit, whereas for complex **3**, bearing chiral ligand L^2, the full dimer appears in the asymmetric unit. Molecular structures (Figures 2 and 3) confirm four-membered metallaoxetane ring formation with Ir–O distances 2.085(4) Å for **2**; 2.087(6) and 2.098(5) Å for **3**. One chelate bound ligand, the olefinic bond of COD and metallaoxetane ring around Ir constitute each monomer. Oxygen coordination from the metallaoxetane ring of one monomer to the other completes the sixth coordination site of Ir and forms the dimeric, structures (Ir–O = 2.137(5) Å for **2**; 2.105(7) and 2.095(8) Å for **3**).

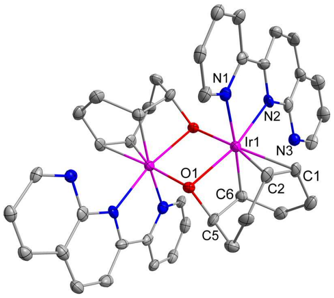


Figure 2. Molecular structure of the dicationic unit $[Ir(C_8H_{12}O)(L^1)]_2$ in **2**.

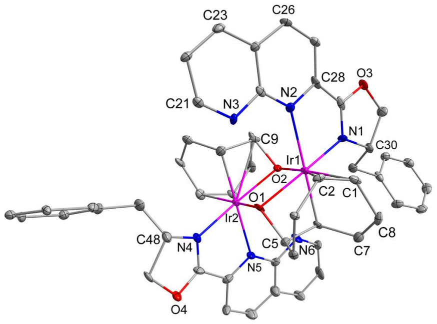


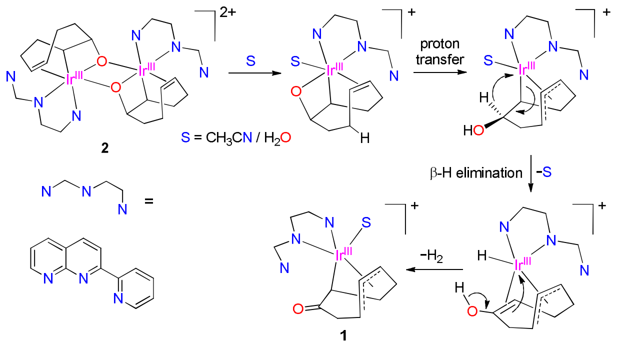
Figure 3. Molecular structure of the dicationic unit $[Ir_2(C_8H_{12}O)_2(L^2)_2]$ in **3**.

Both the complexes are also characterized by ^{1}H-NMR spectroscopy (Figures S6 and S7). For complex **2**, four olefinic CH signals and two Ir-O-CH signals of COD appear in the range between δ = 5.07–5.96 ppm, while complex **3** shows additional oxazoline ring protons and benzylic protons in this region, and appear together in the range between δ = 2.90–5.85 ppm. The ESI-MS of **2** resembles that of **1**, suggesting a rapid conversion under mass spectroscopy conditions, whereas **3** shows a mass peak at *m*/*z* 1361.293 (z=1) corresponding to $[M–OTf]^+$ (Figure S9c).

The intermediacy of metallaoxetanes has been proposed in catalytic homogeneous and heterogeneous olefin oxygenation processes.[13] A handful of metallaoxetane and hydroxy-metalla-allyl compounds are structurally characterized which are accessed via the reaction of metal-bound COD with H_2O_2 or molecular oxygen (For selected examples, See Scheme S1).[14] Klemperer and co-workers reported oxidation of $[Ir(P_3O_9)(COD)]^{2-}$ by molecular oxygen to give a four-membered 2-iridaoxetane intermediate, which upon thermal treatment, rearranges to more stable 5-hydroxy-6-irida(1,2,3)-allyl complex.[15] Following a similar reaction between $[Rh(PhN_3Ph)(COD)]$ and molecular oxygen, Tejel and coworkers were able to isolate 2-rhodaoxetane as a dimer, which after rearrangement gives a polymeric hydroxy-allyl complex in solution.[16] The formation and reactivity of 3-rhoda-1,2-dioxolane and 2-rhodaoxetane were extensively studied by Gal and coworkers.[17] The simplest 2-rhodaoxetane was obtained by the reaction of Rh(I)-ethylene complex with H_2O_2.[17a]

COD oxygenation with water, assisted by naphthyridine ligands, appears to be a reliable reaction. The use of L^3 following a protocol identical to the synthesis of **1** afforded an oxo-irida-allyl complex **4** which is characterized by X-ray crystallography (see Figure S17, SI) as well as other spectroscopic techniques. The nature of products clearly depends on the type of ligands used. Both iridaoxetane **2** and oxo-irida-allyl **1** were isolated for L^1. Iridaoxetane **3** and oxo-irida-allyl compound **4** were obtained exclusively from L^2 and L^3, respectively. Compound **2**, which was isolated by careful manipulation of the reaction conditions, further converted to **1** over time with the evolution of dihydrogen gas. The evolution of H_2 was confirmed by GC.[18] It is therefore prudent to assume that the formation of the oxo-irida-allyl compound proceeds through the metallaoxetane intermediate. A tentative mechanism is proposed in Scheme 3. In coordinating solvent, the metallaoxetane dimer dissociates into two monomers.[19] Allyl proton transfer to the oxetane oxygen gives the hydroxy-metalla-allyl complex,[16,20] which undergoes β-hydride elimination followed by dehydrogenation to afford the oxo-metalla-allyl compound. The proposed mechanism explains why metallaoxetane product is obtained when allylic proton is absent.[17a] Furthermore, use of a tris-chelate capping ligand blocks the *cis* position necessary for β-hydride elimination, causing the reaction to cease at the hydroxy-metalla-allyl stage.[15] In the present study, L^2 ligand possessing a bulky benzyl substituent impedes structural reorganization of the COD unit, preventing allyl proton transfer and subsequent β-hydride elimination. The final product is thus the metallaoxetane product **3**, despite the presence of COD allyl proton. Prolonged reaction time or heating in acetonitrile do not convert **3** to the corresponding oxo analogue. For L^1 and L^3, where no such steric hindrances arise, the corresponding oxo-metalla-allyl complexes **1** and **4**, respectively, are obtained.

Scheme 3. Conversion of metallaoxetane to oxo-metalla-allyl complex.



A strict anaerobic condition was maintained to exclude the possibility of dioxygen in the reaction mixture. Nonetheless, to confirm the source of oxygen, synthesis of **1** was carried out with H_2O^{18}. The product was subjected to high resolution mass spectrometry and IR analysis. On the basis of the masses and isotopic distribution patterns, the signals at *m/z* = 524.123, 565.149 and 585.172 are assigned for $[Ir(L^1)(C_8H_{10}O^{18})]^+$, $[Ir(L^1)(C_8H_{10}O^{18})(CH_3CN)]^+$ and $[Ir(L^1)(C_8H_{10}O^{18})(CH_3CN)(H_2O^{18})]^+$, respectively (Figure 4), which reveal a two unit increase of mass for the first two cases and four unit increase of mass for the last case, compared to O^{16} analogue of **1**. The CO stretching band at 1666 cm^{-1} for complex **1** shifted to the lower energy region at 1645 cm^{-1}, a shift of 21 cm^{-1}, which is attributed to isotopic replacement (Figure S12). These studies clearly show O^{18} incorporation in the final product the source of which is H_2O^{18}.

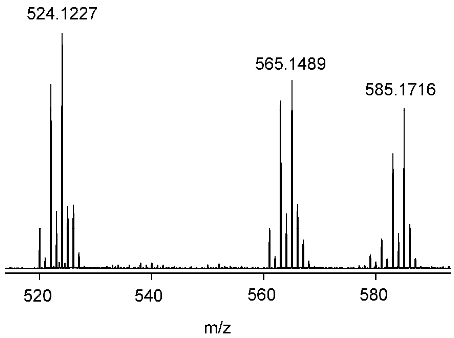


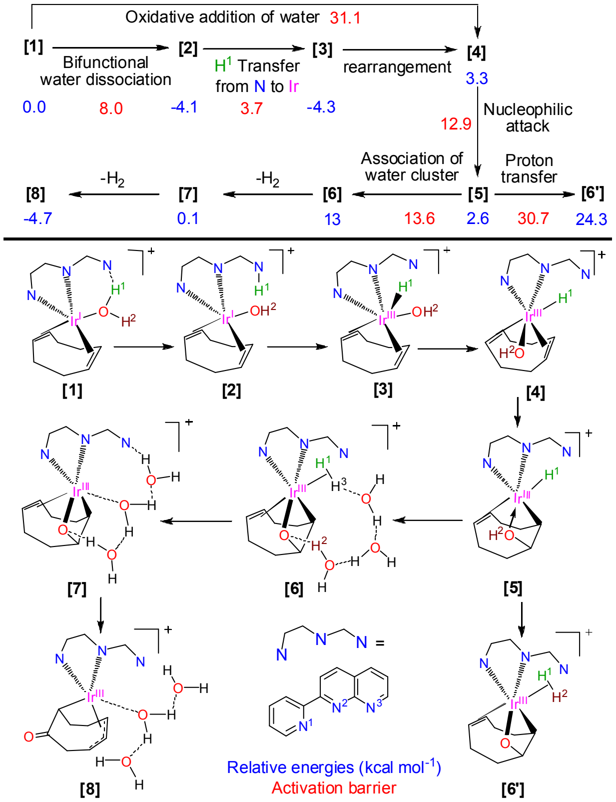
Figure 4. ESI-MS spectrum of O^{18} analogue of **1**

The free nitrogen present in the ligand architecture plays a crucial role for heterolytic water dissociation and subsequent oxygenation process.[2a] Under identical reaction condition, the bipyridine (bpy) analogue [Ir(bpy)(COD)][OTf] (Figure S18, SI), which lacks a free nitrogen, does not react with water to give the COD-oxygenated product. A reaction pathway for metallaoxetane formation supported by DFT calculations is given in Scheme 4. Optimized structures of the intermediates and the transition states are collected in Figure S19, and a computed energy profile in acetonitrile is given in Figure S20. A water adduct $[Ir(pyNP)(COD)(H_2O)]^+$ [**1**] is calculated on the potential energy surface (PES) where water is coordinated to the metal (Ir–O = 2.109 Å) and simultaneously hydrogen bonded to the free nitrogen N^3 of the naphthyridine unit ($N^3\cdots H^1$ = 1.982 Å). Migration of the water proton (H^1) to the naphthyridine nitrogen affords a metal hydroxy species [**2**], (Ir–O = 2.051 Å, N^3–H^1 = 1.038 Å). This is an exothermic process by −4.1 kcal mol^{-1} and requires small activation energy barrier (ΔE_a) of 8.0 kcal mol^{-1}. Subsequent proton shift from the naphthyridine to the metal center leads to an Ir^{III}–hydride intermediate [**3**] with Ir–H/OH distances 1.546/2.049 Å, respectively. Formation of [**3**] is a slightly downhill process by 0.2 kcal mol^{-1}, and the ΔE_a is 3.7 kcal mol^{-1}. An alternative proton shift at a later stage after the hydroxy attack to COD is, however, an energetically uphill process (Scheme S2, Figure S21). The next logical step is nucleophilic attack of the hydroxide to one of the COD double bonds. The hydroxide in [**3**] is not suitably disposed for such attack, but isomer [**4**] conversely is. The rearrangement of [**3**]→[**4**] can be envisioned as a multi-step process involving rearrangement of hydroxide and hydride around the metal center, an uphill process by 7.6 kcal mol^{-1}. A direct oxidative addition of H_2O at the metal to yield the species [**4**] is an energetically difficult process with very high ΔE_a (31.1 kcal mol^{-1}). Ligand assisted water dissociation is thus computed to be a favorable process compared to the direct oxidative addition.

The nucleophilic attack of hydroxy to the metal-bound olefinic double bond leads to the intermediate [**5**], featuring a four-membered metallacycle. A normal mode analysis of TS [**4–5**] confirms this transformation. The ΔE_a and relative reaction energies are 12.9 and −0.7 kcal mol^{-1}, respectively. A similar reaction with D_2O didn't afford deuterium incorporated product as evidenced from the ^{13}C NMR spectrum (Figure S5) and ESI-MS discounting the possibility of a competitive hydride migration to the olefinic double bond.

For the oxetane ring formation, a proton shift from O–H to the metal is expected which would essentially lead to an Ir-dihydrogen complex [**6′**]. This transformation [**5**]→[**6′**] is found to be a highly endothermic process and demands very high ΔE_a= 30.7 kcal mol^{-1}. Since the reaction includes water, a model was designed to calculate the same proton shift step via water cluster. The proton shuttling via the water cluster is anticipated to release the strains of the four-membered transition structure [**5–6′**] and hence lower the activation barrier. The new barrier for [**5**]→[**6**] is reduced to 13.6 kcal mol^{-1}. The pertinent TS structure [**5–6**] includes three water molecules. The resultant product [**6**] is a dihydrogen complex (Ir–H^1/H^3 = 1.782/1.754 Å, H^1–H^3 = 0.841 Å). Removal of H_2 from [**6**] is an exothermic process and leads to the oxetane monomer [**7**]. Overall, the transformation of [**1**]→[**7**] is merely an isothermal process in acetonitrile. Further removal of H_2 from [**7**] is an exothermic process and yields the stable oxo complex [**8**]. Transformation of [**7**]→[**8**] is a complex process as proposed in Scheme 3, and not explicitly studied here by DFT.

Scheme 4. Proposed reaction pathway for 2-iridaoxetane formation by H_2O.



In conclusion, we present here the first report of COD oxygenation by water on an iridium center aided by an unbound nitrogen atom on the naphthyridine ligand. Metallaoxetane and oxo-metalla-allyl compounds, which are potential intermediates in the catalytic oxygenation process, are isolated with dihydrogen as the side product. The steric bulk and rigidity of the ligands dictate the nature of the products. A ligand assisted water activation pathway is proposed supported by DFT studies. The challenge remains to make this reaction catalytically viable.

ASSOCIATED CONTENT

Supporting Information

Detailed experimental procedures, supporting schemes and figures, and crystallographic table. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

‡These authors contributed equally to this work.

Notes

The authors declare no competing financial interests.

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(12) $[Ir(COD)(L^1)](OTf)$ is isolated and characterized by single crystal X-ray diffraction study (see, Figure S13, SI).

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(18) Calculated amount of $[IrCl(COD)]_2$, TlOTf and L^1 were taken in 5ml acetonitrile in a sealed reaction vessel. 10 fold excess of degassed, deionized water was added and the reaction mixture was allowed to stir at room temperature. The evolved gas was injected into the GC instrument. H_2 was identified by comparing with the retention time of the authentic sample.

(19) ESI-MS of **3** in acetonitrile reveals a major signal (100%) for $[Ir(C_8H_8O)(L^2)]^+$ along with a minor signal (<2%) for dimer suggesting dissociation in solution (see, Figure S11, SI).

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