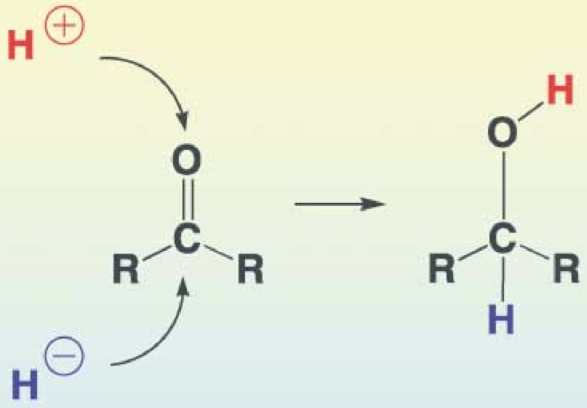
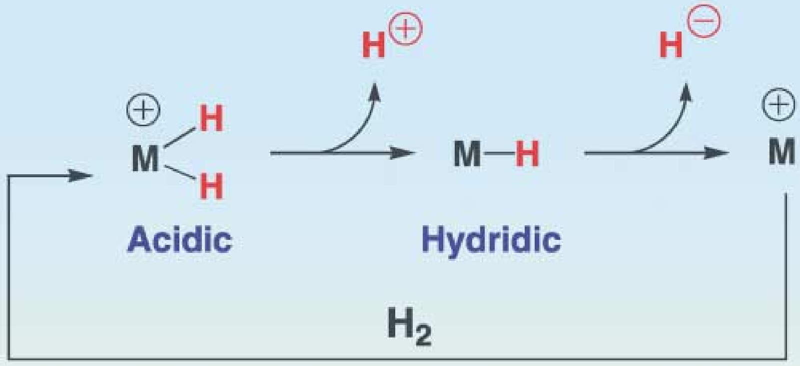
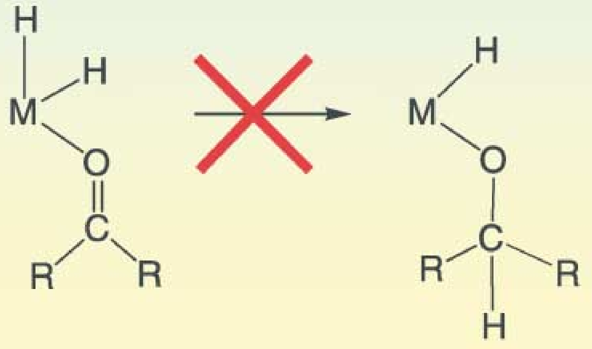
Catalytic Ionic Hydrogenations



$$H_2 = H^+ + H^-$$





Insertion Not Needed

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Catalytic Ionic Hydrogenations

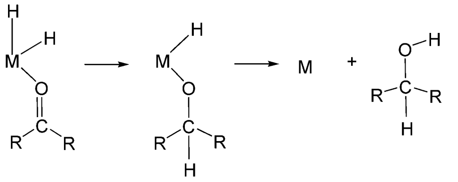
R. Morris Bullock*[a]

Abstract: Catalytic ionic hydrogenation of ketones occurs by proton transfer to a ketone from a cationic metal dihydride, followed by hydride transfer from a neutral metal hydride. This contrasts with traditional catalysts for ketone hydrogenation that require binding of the ketone to the metal and subsequent insertion of the ketone into a M−H bond. Ionic hydrogenation catalysts based on the inexpensive metals molybdenum and tungsten have been developed based on mechanistic understanding of the individual steps required in the catalytic reaction.

Keywords: homogeneous catalysis • hydride ligands • hydride transfer • hydrogenation • protonation

Introduction

Hydrogenations occupy a pivotal role in organometallic chemistry and homogeneous catalysis. From a practical perspective, hydrogenations of C=C and C=O bonds are used widely, and are particularly prevalent in the synthesis of fine chemicals as well as compounds of interest to the pharmaceutical and agricultural industries (i.e., making drugs and killing bugs). In addition to these applications to catalysis, hydrogenations have captured the interest of academic researchers for several decades. A communication in 1961 by Halpern, Harrod, and James noted that while a variety of metal complexes had been shown to activate H_2 and to reduce inorganic complexes, they had "not, in general, proved effective catalysts for the hydrogenation of olefinic compounds."[1] They reported Ru^{II} complexes that catalyzed the hydrogenation of C=C bonds of maleic acid and related compounds. Landmark discoveries followed, such as the report in 1970 by Schrock and Osborn of cationic Rh catalysts for hydrogenation of the C=O bond of ketones.[2] Progress in catalytic hydrogenations was so remarkable that by 1973 Brian James had written an entire book[3] devoted to "Homogeneous Hydrogenation." While many subtle mechanistic details were elucidated,[4] a pervasive mechanistic feature exhibited by nearly all of these catalysts is that two key steps are 1) binding of the unsaturated substrate to the metal, and 2) subsequent insertion of that substrate into a metal hydride bond (M−H), as shown in generalized form in Equation (1) for the case of ketone hydrogenation.



(1)

But are binding and insertion really required? We sought to use mechanistic and kinetic information to design homogeneous hydrogenation catalysts that would function by unconventional mechanisms. This article reviews the development of catalytic systems for ionic hydrogenation and shows that most of the individual steps of the catalytic cycle could be separately investigated in stoichiometric reactions. Knowledge of how the individual steps proceed is helpful in assessing their role in the overall catalytic cycle, especially for identifying which steps need to be improved to produce an attractive catalyst system.

Classical homogeneous hydrogenation catalysts are often based on Rh or Ru, as many complexes of these metals readily undergo insertion reactions into their M−H bonds. *If the requirement of insertion reactions is removed, however, the range of metals that may be suitable is expanded to include metals outside of the platinum group.* The use of less expensive metals is a significant advantage, if such catalysts provide sufficient reactivity and lifetime. Inexpensive metals may provide savings not only from lower initial cost, but also from less stringent requirements for catalyst recovery in industrial processes. The cost of the metal is only one of many criteria that influence the overall economics of operat-

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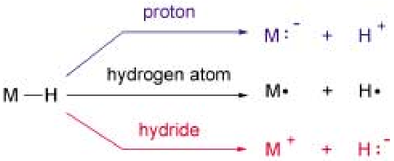
ing a catalytic process, and in many cases expensive phosphanes or other ligands contribute significantly to the cost. Despite this caveat, the quest to develop "Cheap Metals for Noble Tasks" is an attractive goal, both in terms of seeking useful catalysts based on inexpensive metals, and owing to the fundamental mechanistic information that may emanate from studies directed towards such goals. Several examples of catalysts for hydrogenation of C=C bonds based on inexpensive metals were known before our work on ketone hydrogenations.[5]

Proton- and Hydride-Transfer Capabilities of Metal Hydrides

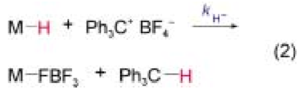
While mechanistic studies have been used to discern details of the insertion of olefins or ketones into M–H bonds, fundamental kinetic and mechanistic studies have been used to examine the modes of M–H bond cleavage. One of the fascinating aspects of metal hydrides is the diversity of their reactivity patterns.[6] In terms of elementary pathways, metal–hydride bonds can be cleaved by all three of the formal bond rupture modes shown in Scheme 1. This scheme may be considered oversimplified, since it does not show the reagent that reacts with the M–H bond to form a C–H, O–H, N–H, or other bond; it is not meant to imply that a "free" hydride, proton, or hydrogen atom is released into solution. The versatility of reactivity patterns is not only significant for metal hydrides as a class, but there are several examples whereby the *same* metal hydride can exhibit *each* of these three formal modes of M–H bond cleavage. Metal hydrides such as $[W(Cp)(CO)_3H]$, $[Mo(Cp)(CO)_2(PPh_3)H]$, $[Re(CO)_5H]$, and others can undergo cleavage of their M–H bond as a proton, as a hydrogen atom, or as a hydride, in reactions with different substrates. Being able to control and rationally modify the rates of such reactions is an important goal in the design of metal hydride reactivity.



Scheme 1. Modes of bond cleavage of metal hydrides.

The availability of proton-[7] and hydride-transfer reactions[8] of metal hydrides suggests the possibility of transition-metal-catalyzed ionic hydrogenations of organic substrates, if the overall addition of H_2 could be carried out in steps involving delivery of H^+ and H^-. Conventional nomenclature calls all complexes with a bond between a metal and hydrogen "metal hydrides"; but the name does not imply that all of them will exhibit hydridic reactivity. Indeed, metal hydrides exhibit a wide range of kinetic and thermodynamic acidity.[7] From Norton's measurements in CH_3CN, the pK_a of 8.3 determined for $[CoH(CO)_4]$ indicates that it is of comparable acidity to HCl in that solvent.[9] The molybdenum hydride $[Mo(Cp)(CO)_3H]$ is less acidic, with a pK_a of 13.9.[9] Tilset and co-workers found[10] that one-electron oxidation of metal hydrides can produce super-acids, with a pK_a of −6.0 estimated in CH_3CN for the radical-cation complex $[Mo(Cp)(CO)_3H]^{+\cdot}$. For our purposes, we need a dihydride or dihydrogen complex as the proton donor rather than a monohydride, and it is abundantly clear that such complexes can have ample acidity.[11]

Quantitative studies have also determined the hydricity of metal hydride complexes. DuBois, Curtis, and co-workers reported thermodynamic measurements of heterolytic cleavage of M–H bonds as H^-, and found that the hydricity spans over 30 kcal mol^{-1}.[12,13] Extensive reactivity studies[14] by Darensbourg and co-workers documented the versatile hydridic reactions of anionic tungsten hydrides like $[W(CO)_5(PPh_3)H]^-$, and recent measurements by DuBois provided a quantitative measure of the high hydricity.[13] The thermodynamic hydricity of this anionic hydride is 29 kcal mol^{-1} greater than than that of the cationic cobalt dihydride $[CoH_2(dppe)_2]^+$[15] This cobalt hydride, with four electron-donating phosphane ligands, is much less hydridic than the tungsten complex containing only one phosphane ligand, indicating that the charge on the complex and changes in the metal play a major role in hydridic reactivity, in addition to electronic and steric effects of the ligands. We determined the kinetics of hydride transfer from a series of metal–carbonyl hydrides to $Ph_3C^+BF_4^-$ in CH_2Cl_2 [Eq. (2)] and found a range of kinetic hydricity that spans about seven orders of magnitude.[16] The molybdenum hydride $[Mo(Cp)(CO)_2(PMe_3)H]$, with an electron-donating phosphane, exhibits high hydricity ($k_{H^-} = 4.6\times10^6\,\mathrm{M^{-1}\,s^{-1}}$ at 25 °C), whereas the tungsten hydride with no phosphane, but an electron-withdrawing substituent on its Cp ring, $[W(C_5H_4CO_2Me)(CO)_3H]$, exhibits a much lower kinetic hydricity ($k_{H^-} = 0.72\,\mathrm{M^{-1}\,s^{-1}}$).

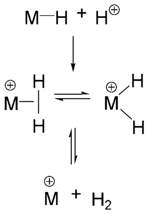


$$M{-}H + Ph_3C^+BF_4^- \xrightarrow{k_{H^-}} M{-}FBF_3 + Ph_3C{-}H \qquad (2)$$

Stoichometric Ionic Hydrogenations with An External Acid as the Proton Donor and a Metal Hydride as the Hydride Donor

Long before our work on transition-metal hydrides, Kursanov and co-workers had developed ionic hydrogenations using stoichiometric quantities of CF_3CO_2H as the acid, coupled with $HSiEt_3$ as the hydride-transfer reagent. An authoritative review published in 1974 documents the utility of this process for stoichiometric hydrogenation of a variety of C=C and C=O bonds.[17] The advantage of using transition-metal hydride complexes is due to potential of developing catalytic cycles in which H_2 can be used as the source of both the H^+ and H^-.

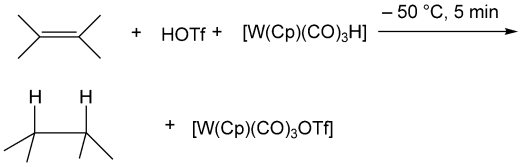
Along with the ability of some metal complexes to produce M–H bonds from reactions with H_2, another advantage of metal hydrides is their reactivity with acids. In contrast to hydrosilanes such as $HSiEt_3$, which immediately evolve hydrogen upon protonation, many transition-metal hydrides can be protonated to give stable products. Protonation at the M–H bond[18] produces a dihydrogen complex[11] in which an H_2 ligand is bound to the metal, while protonation at the metal gives a dihydride complex (Scheme 2).



Scheme 2. Protonation of a metal hydride and subsequent formation of H_2.

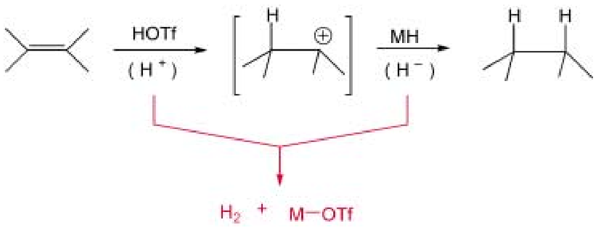
Dihydrogen complexes generally have a higher kinetic acidity compared to the corresponding dihydrides,[11] so this might be expected to favor dihydrogen complexes as proton donors in ionic hydrogenations. It will not necessarily make a big difference whether a dihydride or a dihydrogen complex (or an equilibrium mixture of the two) is the proton donor, as long as this species is sufficiently acidic. The ability of some metal hydrides to serve as a temporary "parking spot" for the proton provides an additional flexibility in the reaction pathways—if the metal is initially protonated rather than the substrate, then the substrate can be protonated by proton transfer from the metal. In either case, hydride transfer from a neutral metal hydride generates the product.

Our initial efforts focused on alkene hydrogenations in which metal hydrides could serve as H^- donors using a stoichiometric amount of acid as the H^+ source. Stoichiometric ionic hydrogenations of alkenes proceed cleanly under mild conditions (−50 °C, 5 minutes) using HOTf (OTf = OSO_2CF_3) and several metal hydrides [Eq. (3)].[19] These hydrogenations work well for tetra-, tri-, and 1,1-disubstituted alkenes; the common feature among these alkenes is that they form tertiary carbenium ions upon protonation. The same limitation was encountered in the ionic hydrogenations of alkenes by CF_3CO_2H and $HSiEt_3$.[17]



(3)

Why do these reactions succeed? Hydridic reactivity of the metal hydride (or hydrosilane) might suggest that the reaction with acid would irreversibly produce H_2 (Scheme 3). To achieve a successful ionic hydrogenation, hydride transfer to the protonated organic substrate must occur faster than production of hydrogen from reaction with acid.

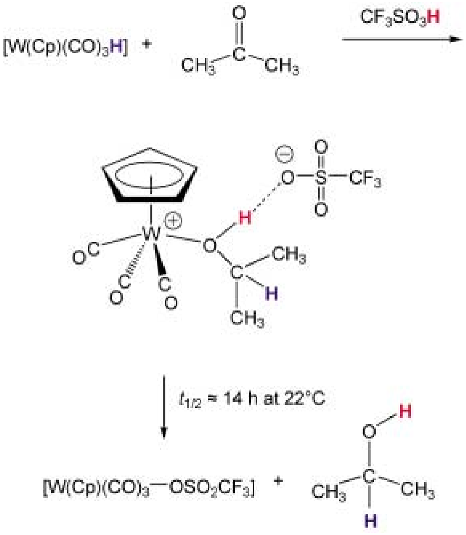


Scheme 3. Stoichiometric ionic hydrogenation of an alkene, and competing loss of H_2.

Our finding that certain alkenes were readily hydrogenated by HOTf/$HSiEt_3$ was surprising. A review of the use of CF_3CO_2H and $HSiEt_3$ had stated that "stronger acids cannot be used in conjunction with silanes because they react."[17] Indeed, H_2 promptly bubbles out of solution when HOTf is added to $HSiEt_3$. This undesired reaction does not preclude ionic hydrogenation reactions from being successful, as long as the order of addition is done correctly. When HOTf is added to a solution containing $HSiEt_3$ and the alkene, the reaction proceeds quickly and cleanly, since the acid protonates the alkene to give a carbenium ion, which then abstracts hydride from the hydrosilane to generate the product. Under such conditions, acid-induced formation of H_2 from $HSiEt_3$ is an insignificant side reaction.

Alkynes can also be hydrogenated by HOTf and [W(Cp)(CO)$_3$H]. For example, PhC≡CH is converted to $PhCH_2CH_3$, but these double ionic hydrogenations of C≡C bonds were not studied for a wide variety of acetylenic substrates.[20]

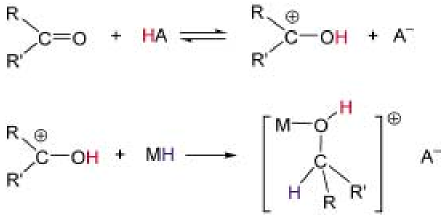
Several examples were known in which stoichiometric hydrogenation of C=O bonds could be carried out by metal hydrides upon reaction with acids.[21] We expected that ketones and aldehydes could be hydrogenated by [W(Cp)(CO)$_3$H] and HOTf to give free alcohols and the metal triflate complex [W(Cp)(CO)$_3$(OTf)]. Our expectation was correct in predicting the *thermodynamic* product, but an unexpected *kinetic* product was discovered (Scheme 4).[22] The reaction of acetone with [W(Cp)(CO)$_3$H]



Scheme 4. Stoichiometric ionic hydrogenation of acetone.

and HOTf gave a complex with an isopropyl alcohol ligand. The alcohol ligand was generated in the hydrogenation reaction without leaving the metal. Most previously reported alcohol complexes had been synthesized by treating a free alcohol with a metal complex containing a weakly coordinating ligand. A series of alcohol complexes were isolated, and crystal structures showed that they had a strong hydrogen bond between the OH group and an oxygen atom of the OTf^- ion.[23] NMR spectra also indicated that the hydrogen bonding was maintained in solution, since the OH resonances in the ^1H NMR were substantially downfield of the OH resonances of free alcohols. The free alcohol is released by displacement of the alcohol ligand by the OTf^- anion, usually on a timescale of several hours at room temperature.

A study of the kinetics of the stoichiometric ionic hydrogenation of aldehydes revealed that the rate of hydrogenation decreased as the reaction proceeded, since the acid was being depleted.[22] When the acidity was held constant by a buffer, the reaction was shown to be second-order overall, first order in aldehyde, and first order in metal hydride. The proposed mechanism that is consistent with all the observations is a pre-equilibrium proton transfer to the substrate, followed by rate-determining hydride transfer, as shown in Scheme 5.

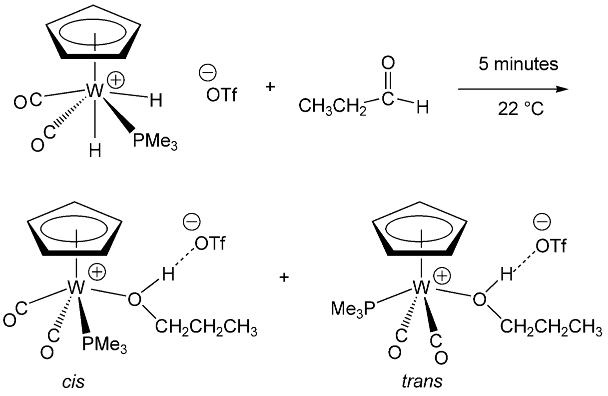


Scheme 5. Mechanism of stoichiometric ionic hydrogenation of an aldehyde or ketone.

Ionic hydrogenations of other substrates expanded the scope of the reaction, and resulted in new complexes in which the hydrogenated organic product is bound to the tungsten in the kinetically stabilized product. Reaction of α,β-unsaturated ketones with $[W(Cp)(CO)_3H]$ and HOTf results in hydrogenation of the C=C bond, and formation of $[W(Cp)(CO)_3(\eta^1\text{-ketone})]^+[OTf]^-$ complexes as the product.[24] The reaction of the acyl chloride PhC(=O)Cl with $[W(Cp)(CO)_3H]$ and HOTf produces the aldehyde complex $[W(Cp)(CO)_3(\eta^1\text{-PhCHO})]^+[OTf]^-$ and HCl.[24] Coordinated ethers were formed in the reaction of acetals, as shown for the formation of $[W(Cp)(CO)_3(PhCH_2OCH_3)]^+[OTf]^-$ from the reaction of $PhCH(OCH_3)_2$ with $[W(Cp)(CO)_3H]$ and HOTf.[25]

Stoichiometric Hydrogenations with Metal Hydrides as both Proton and Hydride Donors

The effectiveness of H^--transfer reactions of metal hydrides with an *external* acid as the H^+ donor was documented in the reactions described above. To move towards a catalytic system required that we find a metal-based source of protons, so that ultimately both the H^+ and the H^- could be derived from H_2. We found that when aldehydes or ketones are added to the tungsten dihydride complex $[W(Cp)(CO)_2(PMe_3)(H)_2]^+$,[23] stoichiometric hydrogenation occurs within a few minutes at room temperature [Eq. (4)].



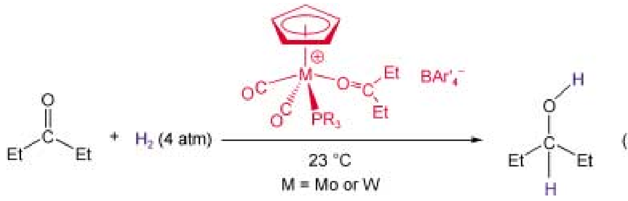
(4)

The initial products of the hydrogenation are *cis*- and *trans*-isomers of the alcohol complex $[W(Cp)(CO)_2(PMe_3)(ROH)]^+$, which then release the alcohol slowly, as expected by the precedent shown in Scheme 4. The stoichiometric ionic hydrogenations proceeded as desired, with an H^+ transfer from a cationic dihydride to the oxygen being followed by an H^- transfer from the neutral metal hydride to the carbon atom.

Tilset and co-workers used low-temperature NMR spectroscopy to show that $[W(Cp)(CO)_2(PMe_3)(H)_2]^+$ was a dihydride rather than a dihydrogen complex.[10] Our characterization of $[W(Cp)(CO)_2(PMe_3)(H)_2]^+[OTf]^-$ by X-ray crystallography provided further evidence that it has two nonequivalent W–H bonds in the solid state.[26] While these studies made it clear that the dihydride form is thermodynamically favored, kinetics studies by Norton and co-workers led to the conclusion that the protonation at the M–H bond (to give a dihydrogen complex) is faster than direct protonation at the metal to give the dihydride.[27] Protonations of this type[18] represent the microscopic reverse of deprotonations of dihydrogen complexes, which are known to be kinetically preferred over deprotonation of the corresponding dihydrides.[11] For the Mo analogue, Poli and co-workers observed prompt evolution of H_2 when $[Mo(Cp)(CO)_2(PMe_3)H]$ was protonated at −78 °C; they suggested the formation of an unstable molybdenum–dihydrogen complex to account for these results.[28] Furthermore, Poli showed that the structure of $[Mo(Cp)(CO)_2(PMe_3)(AuPPh_3)_2]^+$ has an Au–Au interaction; use of the isolobal analogy between H and $AuPPh_3$ makes this complex pertinent to the putative molybdenum–dihydrogen complex.[29] Norton determined that the pK_a of $[W(Cp)(CO)_2(PMe_3)(H)_2]^+$ in CH_3CN was 5.6.[27] Comparison of this value with the pK_a of about −0.1 in CH_3CN for protonated acetone,[30] $[Me_2C{=}OH]^+$, indicates that the protonation a ketone or aldehyde by $[W(Cp)(CO)_2(PMe_3)(H)_2]^+$ is significantly uphill thermodynamically. The hydrogenation does proceed cleanly, however, since the proton transfer step is followed by a fast hydride transfer from the neutral metal hydride [Eq. (4)].

Closing the Catalytic Cycle: Regeneration of M−H Bonds by Reaction with H_2

These results provide a metal-based source of both H^+ and H^-, but completion of the catalytic cycle requires that H_2 react with a metal complex, so that both M−H bonds can be derived from H_2. A series of Mo and W complexes of formula $[W(Cp)(CO)_2(PR_3)(O{=}CEt_2)]^+BAr'^-_4$ [Ar′ = 3,5-bis(trifluoromethyl)phenyl] were shown to serve as catalyst precursors for the ionic hydrogenation of ketones [Eq. (5)], with the molybdenum complexes giving faster rates of catalysis than the tungsten analogues.[31] Under the mild conditions of 23 °C and 4 atm H_2, the rates are slow, with a maximum of about 2 turnovers/hour for M = Mo and $PR_3 = PCy_3$ (Cy = cyclohexyl). The proposed mechanism is shown in Scheme 6. For these ionic hydrogenations of $Et_2C{=}O$, the main species observed during the reactions are the ketone complexes, with increasing amounts of the alcohol complexes $[W(Cp)(CO)_2(PR_3)(Et_2CHOH)]^+$ being directly observed by NMR spectroscopy as the hydrogenation proceeds. In most cases the turnover-limiting step of the catalytic cycle is displacement of the ketone (or alcohol) ligand by H_2 to form the dihydride. For both the Mo and W complexes, the rates increase with the steric bulk of the phosphane with the order of catalytic activity being $PCy_3 > PPh_3 > PMe_3$. The faster rate obtained for PCy_3 relative to PMe_3 is particularly informative for identifying the beneficial effect of steric bulk of the phosphane ligand, since these two phosphanes are similar electronically. Phosphonium cations (HPR_3^+) are observed in the reaction mixtures, indicating that dissociation of phosphane (and subsequent protonation) is a major mode of decomposition of these catalysts.



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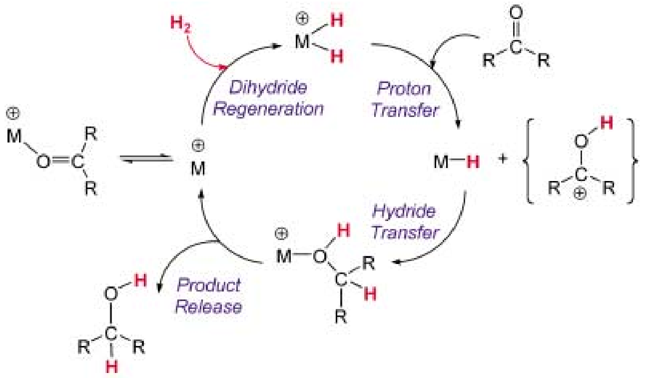
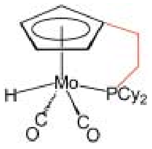
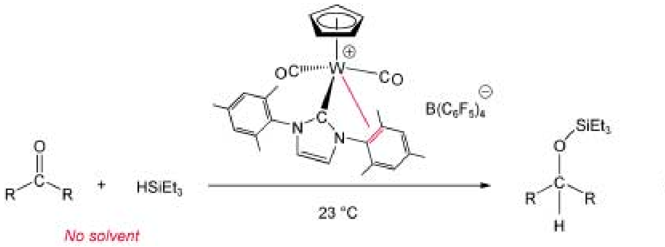


Scheme 6. Proposed mechanism for catalytic ionic hydrogenation of ketones.

The observation of this decomposition pathway led us to synthesize a new generation of catalysts with improved lifetimes. Suppression of phosphane dissociation was sought by using a two-carbon bridge to chelate the phosphane to the cyclopentadienyl ligand. Substantially improved performance was found using catalysts obtained by reaction of $[MoH(CO)_2\{\eta^5{:}\eta^1\text{-}C_5H_4(CH_2)_2PR_2\}]$ (R = Ph, Cy, *t*Bu) with $Ph_3C^+BAr'^-_4$.[32] Hydrogenation of liquid ketones can be carried out under solvent-free conditions at low catalyst loadings. For example, neat $Et_2C{=}O$ was completely hydrogenated to the alcohol (eight days at 50 °C, 55 atm H_2 pressure) using $[MoH(CO)_2\{\eta^5{:}\eta^1\text{-}C_5H_4(CH_2)_2PCy_2\}]$ (0.35 mol %) as the catalyst precursor.

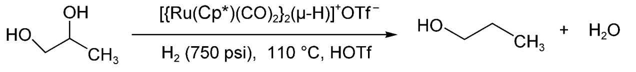


Tungsten catalysts with *N*-heterocyclic carbene ligands rather than phosphane ligands were recently prepared. They catalyze hydrogenation of ketones, but they still suffer some decomposition resulting from dissociation of the carbene ligand.[33] These same tungsten–carbene complexes catalyze the hydrosilylation of ketones [Eq. (6)], and exhibit an unusual property—in the hydrosilylation of aliphatic substrates, the catalyst precipitates at the end of the reaction.[34] The hydrosilylations are carried out under solvent-free conditions, using the ketone and $HSiEt_3$ as solvent. The conversion to the alkoxysilane product produces a substantial decrease in polarity of the medium; the catalyst precipitates and can be readily recovered and used again. The proposed mechanism for the hydrosilylations is related to that shown in Scheme 6 for hydrogenations, except that the first step forms a strong Si−O bond rather than an O−H bond. The complex $[W(Cp)(CO)_2(IMes)(SiEt_3)H]^+[B(C_6F_5)_4]^-$ (IMes = the carbene ligand 1,3-bis(2,4,6-trimethylphenyl)-imidazol-2-ylidene) is a resting state of the reaction.



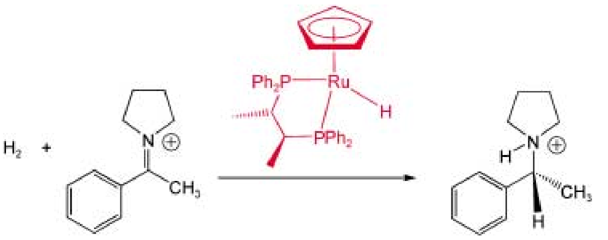
(6)

Catalytic ionic hydrogenations are involved as the product-forming step of the catalytic selective deoxygenation of 1,2-propanediol to *n*-propanol[35] [Eq. (7)] The initial step of the deoxygenation of diols is dehydration of the diol to give an aldehyde, which then undergoes ionic hydrogenation to give the alcohol product. Following the recognition of this hydrogenation step in the deoxygenation reaction, it was independently shown that aldehydes and ketones are hydrogenated using $[\{Ru(Cp^*)(CO)_2\}_2(\mu\text{-}H)]^+OTf^-$ as a catalyst precursor under H_2. This apparently occurs through the formation of the dihydrogen complex $[Ru(Cp^*)(CO)_2(H_2)]^+$, formed under the reaction conditions from the bimetallic complex under H_2 in the presence of HOTf. Heinekey had found the dihydrogen complex $[Ru(Cp^*)(CO)_2(H_2)]^+$ to be very acidic, being deprotonated by Et_2O.[36] We subsequently determined that the neutral hydride $[Ru(Cp^*)(CO)_2H]$ was a very efficient hydride-transfer reagent.[37] Thus the $[Ru(Cp^*)(CO)_2]^+$ moiety has exactly the characteristics needed in ionic hydrogenations—it forms a dihydrogen complex of high acidity and a neutral hydride with high hydricity.



(7)

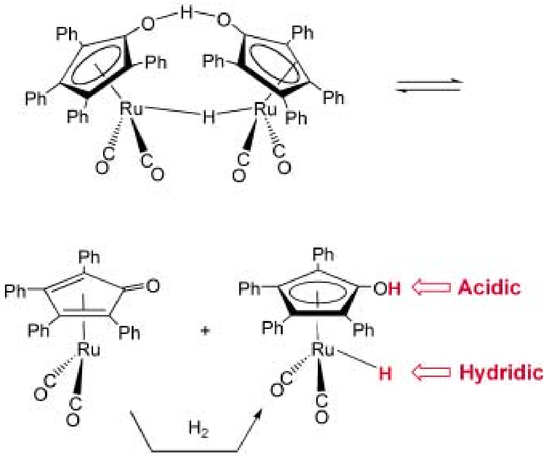
Norton found Ru complexes with chiral diphosphanes that operate by an ionic hydrogenation mechanism to catalyze the enantioselective hydrogenation of C=N double bonds of iminium cations [Eq. (8)].[38] The proposed mechanism is related to that shown in Scheme 6 for ketone hydrogenations. Hydride transfer to the iminium cation starting material produces an amine. Reaction of H_2 with the metal generates the Ru–dihydrogen complex, which transfers a proton to the amine, generating the observed product. The enantiomeric excess (*ee*) obtained under these catalytic conditions was similar to those found when stoichiometric hydride-transfer reactions from the ruthenium hydrides were separately investigated. No dependence on the rate or *ee* was found when the hydrogen pressure was varied, and the neutral ruthenium hydride was observed when the reaction was monitored under H_2 pressure in an NMR tube. These observations lead to the conclusion that hydride transfer is the turnover-limiting and enantioselectivity-determining step of the catalytic cycle. The kinetics of the hydride-transfer step were studied separately, and it was shown that the rate constant is higher when the chelate ring size is smaller.[39]



(8)

Ionic Hydrogenations with OH or NH as Proton Donors and Metal Hydrides as Hydride Donors

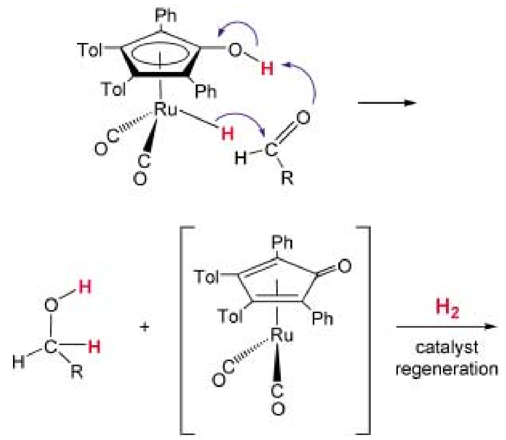
Our studies were designed to exploit the capability of H^+ and H^- transfers from M–H bonds. Different types of catalysts have been discovered that appear to proceed through ionic mechanisms in which the source of the proton is an NH or an OH bond, and the hydride is delivered from a metal hydride. Shvo and co-workers reported a bimetallic ruthenium complex that catalyzes the hydrogenation of aldehydes, alkenes, and alkynes.[40] The catalyst precursor has the two metals joined by a bridging hydride, and an O–H–O hydrogen bond connects the two cyclopentadienone ligands (Scheme 7). Catalytic hydrogenation of ketones occurs at 145 °C under 500 psi H_2 pressure. Cleavage of the bimetallic starting material would produce a formally 16-electron Ru fragment along with the 18-electron Ru–hydride containing the substituted hydroxycyclopentadienyl ligand. Addition of H_2 to the former produces the latter. Casey and co-workers reported a detailed kinetic and mechanistic study of this type of complex; they provided evidence for concerted delivery of H^+ from the OH and H^- transfer from the RuH site, as depicted in Scheme 8.[41] The hydrogenation occurs at temperatures below 0 °C; the much higher temperature used in the catalytic reaction starting from the bimetallic precursor is required to generate the mononuclear species that actually carries out the hydrogenation.



Scheme 7. Shvo's bimetallic ruthenium catalyst precursor and catalyst.

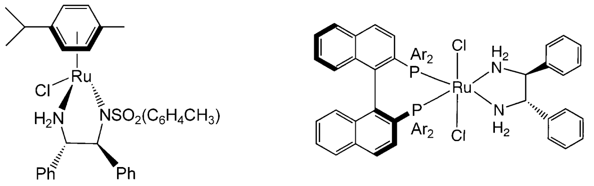
Bäckvall and co-workers found that the Shvo catalyst can be used at 70 °C for the transfer hydrogenation of imines.[42] In transfer hydrogenations, the two H atoms are derived from an organic compound (often isopropyl alcohol), rather than using H_2. The hydrogenation of the C=N bond is accomplished by H^+ from the OH and H^- transfer from the RuH. Regeneration of the OH and RuH sites occurs from the reaction of isopropyl alcohol with the 16-electron complex.

Noyori and co-workers developed highly enantioselective transfer hydrogenation catalysts that exhibit extraordinary turnover rates and lifetimes. Recent reviews document the

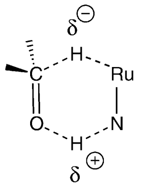


Scheme 8. Concerted delivery of H^+/H^-, and regeneration of the catalyst.

development and wide scope of these remarkable catalysts;[43] comments here focus only on the relevance to ionic hydrogenations. Two of the classes of Ru complexes developed by Noyori's group are shown in Scheme 9. Both of these are catalyst precursors; under the reaction conditions (isopropyl alcohol and a base such as KOH), the active catalyst is formed, containing an RuH and an NH site. The transition state for these metal–ligand bifunctional catalysts was shown computationally to involve a six-membered ring system as in Scheme 10, whereby hydride transfer from RuH and proton transfer from NH occur simultaneously.[44] Morris and co-workers have developed highly reactive Ru catalysts that appear to function by a similar mechanism.[45] Chan and co-workers reported related Ru catalysts that are air-stable, even in solution.[46]



Scheme 9. Two of Noyori's hydrogenation catalyst precursors.



Scheme 10. Computed transition state of Noyori's hydrogenation catalyst.

Conclusion and Outlook

Traditional catalysts for ketone hydrogenation rely on coordination of the ketone to the metal, so that insertion of the ketone into the M–H bond can occur. In contrast, binding of ketone to the metal is not required for ionic hydrogenations. The development of catalytic ionic hydrogenations owes much to kinetic and mechanistic studies that demonstrated the breadth of proton- and hydride-transfer capabilities of metal hydrides. When these modes of M–H bond cleavage are coupled to a mechanism that regenerates M–H bonds through reaction with H_2, catalytic ionic hydrogenation results. The scope and utility of catalytic ionic hydrogenations is yet to be fully defined, but increasing evidence suggests that such mechanisms are becoming more widely recognized, both from catalysts intentionally designed to follow this pathway, and from the recognition that some known catalysts employ ionic mechanisms. We have found stoichiometric reactions that demonstrate the competence of the individual steps in the catalytic reactions, and have assembled metal and ligand combinations that utilize such steps to produce a new type of catalytic system. The resultant Mo and W catalyst are not as active as Ru or Rh catalysts, but ongoing studies are seeking to design catalysts with improved lifetimes and rates.

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