**Hydrogenation Catalysis**

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Hydrogenation is the addition of H2 to a multiple bond (C=C, CC, C=O, C=N, CN, N=O, N=N, NN, etc) to reduce it to a lower bond order. The most common and simple type of hydrogenation is the reduction of a C=C double bond to a saturated alkane:

There are three different ways that transition metal catalysts can activate H2 for performing hydrogenation catalysis:

**Oxidative addition:** the most common method of activating H2 on a metal with d electrons (d2 or higher). Metal center typically needs to have an empty coordination site in order to bind the H2 first, prior to the oxidative addition.

**Hydrogenolysis:** the only way that early transition metals with d0 counts can activate H2. Lanthanides and actinides also typically use hydrogenolysis. As with oxidative addition, the metal center needs to have an empty orbital to bind the H2 and an anionic ligand (e.g., alkyl, halide) that can be protonated off. No change in oxidation state of the metal.

**Heterolytic cleavage:** in many ways quite similar to hydrogenolysis except that the proton produced does not directly react with an anionic ligand coordinated to the metal, but rather with an external base that typically has to transfer it back to the metal center to complete the catalytic cycle. Ru(+2) is the most common metal that uses heterolytic cleavage as a mechanism. No change in oxidation state of the metal.

**Wilkinson’s Catalyst:** RhCl(PPh3)3 was the first highly active homogeneous hydrogenation catalyst and was discovered by Geoffrey Wilkinson (Nobel prize winner for Ferrocene) in 1964. R. Coffey discovered it at about the same time while working for ICI (Imperial Chemical Industries). It was very simply prepared by reacting RhCl3

3H2O with excess PPh3 in EtOH:

The proposed mechanism is as follows:



It has been clearly shown that PPh3 is readily lost due to steric crowding and that the inner catalyst cycle with a weakly coordinated solvent molecule (not shown) is about 1000 times faster than the outer cycle that has 3 PPh3 ligands coordinated to the metal.

This hydrogenation catalyst is compatible with a variety of functional groups (ketones, esters, carboxylic acids, nitriles, nitro groups, and ethers) and indicates that the metal hydride intermediate is primarily covalent in character.

Coordinatively unsaturated cationic catalysts that were considerably more active for hydrogenation were later discovered. The reason for this is that the cationic metal center is more electrophillic and this favors alkene coordination, which is often the rate determining reaction step.



The *ability to coordinate to the catalyst* directly influences the rate of hydrogenation. Thus, unsaturated substrates containing polar functionality which can assist in binding to the catalyst have faster hydrogenation rates. Terminal alkynes are hydrogenated as well and at a faster rate than terminal alkenes (better binding and insertion). The following is the general trend in hydrogenation rates:



Selectivity:

Hydrogenation catalysts typically will selectively hydrogenate the most reactive multiple bonds first. Steric and electronic effects play an important role in this. Consider the following examples:



**Problem: In the molecule below, which of the olefins (A, B, or C) would you expect to hydrogenation faster and why?**



Directing Effects

Crabtree has demonstrated some very interesting substrate directing effects in hydrogenation:



The weak ligand bonding of the OH group on the substrate directs one specific side of the alkene to coordinate to the metal center in order to form an alkene-OH chelate to the Ir.



Group binding affinities: amide > OH > OR > ester ~ ketone



Amine groups bind too strongly and inhibit catalysis. Rigid structures with stronger chelates, like the norbornene ligand shown to the right, are also poor substrates.

For a comprehensive review of cyclic and acyclic substrate-directed hydrogenations see: Hoveyda, Evans, and Fu, *Chem. Rev.* **1993**, *93*, 1307.

**Ru Heterolytic H2 Activation**

Ru has a strong tendency to perform a ***heterolytic activation of H2*** instead of oxidative addition to make a metal dihydride. This can occur either via hydrogenolysis or heterolytic cleavage mechanisms. Complexation of the dihydrogen to the metal leads to a *decrease* in H-H σ-bond character. This decrease in bonding leaves it with a partial positive charge hence making it more *acidic*, or easier to deprotonate with a ‘base’ (either internal or external). Both hydrogenolysis (σ bond metathesis) and heterolytic cleavage mechanism give the same net result:



Shown below is a proposed catalytic cycle for Ru(+2) catalyzed hydrogenation:



Note that there is no change in oxidation state of the Ru(+2)!

**Lanthanide Hydrogenation Catalysts**

Tobin Marks reported the extraordinary activity of (Cp\*2LuH)2 for the hydrogenation of alkenes and alkynes. The monometallic complex catalyzes the hydrogenation of 1-hexene with a TOF = 120,000 hr1 at 1 atm H2, 25ºC!! This is one of the most active hydrogenation catalysts known.

The proposed mechanism is shown below:



**Asymmetric Hydrogenation**

95% of all hydrogenations use heterogeneous catalysts like Pd on carbon (Pd/C) or Raney Nickel. One area where homo­geneous catalysis rules is *asymmetric hydrogenation*. This involves the use of a chiral catalyst and an alkene substrate that generates a chiral carbon center on hydrogenation.

The first dramatic example of this was reported in 1968 by Bill Knowles and coworkers at Monsanto. Knowles found that a bidentate, C2 symmetric version of the cationic Schrock-Osborn catalyst afforded extraordinarily high levels of enantioselectivity in the hydrogenation of -acetamidocinnamatic acid which is used to produce **L**-Dopa, an important pharmaceutical for the treatment of Parkinson’s disease (Knowles, *JACS* **1975**, *97*, 2567). Knowles went on to win the Nobel Prize in 2001, sharing it with B. Sharpless and R. Noyori, for this discovery.



As you can see, the mechanism of this hydrogenation differs from that observed with neutral catalyst ligated with monodentate ligands. That is, olefin complexation occurs *prior* to H2 oxidative addition and this oxidative addition is the rate-limiting step. What is even more amazing is that the major olefin complex diastereomer, which was isolated and characterized by NMR and X-ray techniques, gives the WRONG product. In elegant mechanistic studies, Halpern showed that the *minor diastereomer (olefin complex)* REACTS 580x FASTER to give the final hydrogenated chiral product in a 60:1 ratio!

**Problem: Draw a reaction coordinate diagram that clearly shows the difference in reactivity between the two diastereotopic olefin complexes.**

**Other H-X additions: Hydrosilylation and Hydrocyanation**

**Hydrosilylation (addition of H-SiR3)**

These H-X additions are very similar to hydrogenation (addition of H-X where X=H). Platinum and Palladium catalysts are most widely used for the hydrsilylation of alkenes.



Hydrosilylation of alkynes has been achieved with rhodium and ruthenium catalysts.



**Hydrocyanation (addition of H-CN)**

Hydrocyanation is used industrially to prepare adiponitrile from butadiene. Adiponitrile is the key intermediate in synthesizing Nylon-6,6.



**Problem: Draw a detailed reaction mechanism that shows the conversion of butadiene to adiponitrile.**