7.10: Multisite Redox Enzymes (Part 6)

N_2 and Related Complexes

The triple bond of N_2 has one σ and two πcomponents. Each nitrogen atom has a lone pair oriented along the N-N direction. The two lone pairs allow N_2 to bind in an end-on fashion in either a terminal or a bridging mode. Both modes of binding are illustrated in the binuclear zirconium complex[333] shown in Figure 7.34. In this and in many other N_2 complexes, the N-N bond is not significantly lengthened and is therefore presumed to be insignificantly weakened in the complex. Interestingly, the complex in Figure 7.34, despite not having long N-N distances, forms hydrazine quantitatively upon protonation. Only one of the three N_2 molecules is reduced, and all four electrons required come from the two Zr(III) by presumed internal electron transfer. The related \(\mu])-N_2 complex $[W(\eta^5\text{-}C_5Me_5)Me_2(SC_6H_2Me_3)]_2(\mu\text{-}N_2)$ is one of the few dinitrogen complexes to contain an S donor ligand.[333a]

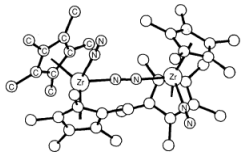


Figure 7.34 - The x-ray crystal structure[333] of $(Cp')_2Zr(N_2)(\mu_2\text{-}N_2)Zr(N_2)(Cp')_2$.

In addition to the N lone pairs, the π components of the N≡N triple bond can serve as donor-acceptor orbitals in the Dewar-Chatt-Duncanson (olefin binding) manner. This less-common mode of N_2 binding is illustrated by the structure of the Ti complex[334] shown in Figure 7.35. Here, as in the few other known side-on bound N_2 complexes,[335] the N-N bond is significantly lengthened. The lengthened bond at 1.30 Å is presumed to be sufficiently weakened [ν(N-N) = 1280 cm^{-1}] that it is susceptible to further lengthening and reduction. As the N-N distance lengthens, it is more appropriate to consider the ligand as a deprotonated diimide or hydrazine.

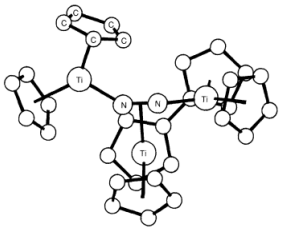


Figure 7.35 - The structure of a multiply bound dinitrogen titanium compound.[334]

Complexes that have proven particularly useful are bis(dinitrogen)phosphines of Mo(0) and W(0) such as $M(N_2)_2(Ph_2PCH_2CH_2PPh_2)_2$ and $M(N_2)_2(PPh_2Me)_4$. As shown in Figure 7.36, treatment of the complexes[336-337a] with acid leads to the formation of the diazenido(-H) and hydrazido(-2H) complexes, and sometimes to the production of ammonia. The finding of a bound $N_2H_2^{2-}$ species is consistent with the proposed presence of similar bound species in nitrogenase. The complexes of reduced dinitrogen intermediates are stabilized by multiple M-N binding. Further protonation of these intermediates or treatment of the original complex with strong acid leads to the formation of NH_3 from the bound nitrogen. Here the Mo(0) starting complex has enough electrons [six from the Mo(0) → Mo(VI) conversion] to reduce one N_2 molecule in conjunction with its protonation from the external solution.

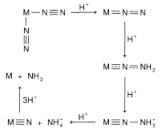


Figure 7.36 - Structure and reactions of $M(N_2)_2(Ph_2PCH_2CH_2PPh_2)_2$ (M = Mo, W) and related complexes. Not all of the intermediates in this scheme have been isolated in anyone particular system.[336,337,337a] The phosphine ligands are not shown.

In a general sense this reaction may be telling us something about nitrogenase. The enzyme may be able to deliver six reducing equivalents to N_2, and protonation, perhaps carefully orchestrated by neighboring amino-acid or homocitrate groupings, may facilitate the process. However, it is virtually certain that the Mo in nitrogenase is not able to change its oxidation state by six units. In the enzyme the multimetal, multisulfur FeMoco site may serve the equivalent function, by providing multiple sites at which reduced intermediates can simultaneously bind.

Only a few of the known N_2 complexes contain S-donor ligands. One of these, $Mo(N_2)_2(S(CH_2C(CH_3)_2CH_2S)_3)$, shown in Figure 7.37, has four thioether S-donor atoms bound to Mo(0). This Mo(0) complex shows reactivity reminiscent of the related phosphine complexes.[337a] A remarkable complex (Figure 7.38) has been isolated[338] in which two lone pairs of *trans*-diimide bind to two Fe, concomitantly with H-binding of the two diimide hydrogen atoms to coordinated sulfur atoms. The ability of an Fe-S system to stabilize the very reactive trans-N_2H_2 grouping adds support to the notion that similar metal-sulfide sites of nitrogenase may stabilize related intermediates along the $N_2 \rightarrow 2NH_3$ reaction path.

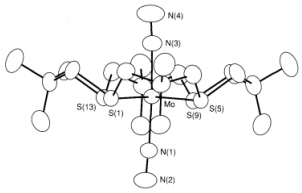


Figure 7.37 - The structure of $Mo(N_2)_2L$ (L is a tetrathiacyclohexadecane)[337b,c]

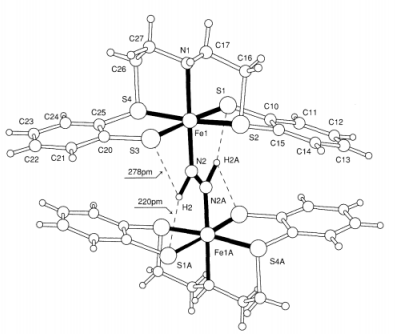


Figure 738 - The structure[338] of FeL(N_2H_2)FeL (L = $SC_6H_4SCH_2CH_2SCHCH_2SC_6H_4S$).

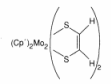
Most of the model systems involving N_2 do not lead to NH_3 formation. Moreover, many systems that do form NH_3 are not catalytic. However, certain V-based and Mo-based systems can catalytically reduce N_2 to N_2H_4 or NH_3 using strong reducing agents.[339] Although kinetic studies indicate the possibility of intermediates, little structural information is available at present on these interesting systems.

Insights from Relevant Inorganic Reactivity

Certain studies on inorganic systems that do not model the nitrogen-fixation process can nevertheless potentially give insight into nitrogenase action. Two categories of relevant chemistry are acetylene binding/reactivity and dihydrogen binding/activation. Modes of dihydrogen activation on sulfide systems have previously been discussed in the section on hydrogenase.

Acetylene has long been known to bind to metal centers using its $\pi$and π^* orbitals as, respectively, σ-donor and \(\pi)-acceptor orbitals. Even when the metal is predominantly sulfur-coordinated,[340,341] such side-on bonding of RC_2R is well known[340,341] as in $MoO(S_2CNR_2)_2(RC{\equiv}CR)$ and $Mo(S_2CNR_2)_2(RC{\equiv}CR)_2$. The direct interaction of acetylene with the metal center must be considered as a potential binding mode for nitrogenase substrates.

A totally different, sulfur-based mode of acetylene binding is now also well established. For example, $(Cp')_2Mo_2S_4$ reacts with acetylene[342,225] to produce



(7.18)

containing a bridging ethylene-1,2-dithiolate (dithiolene). The acetylene binds directly to the sulfur atoms by forming S—C bonds. Acetylenes or substituted (activated) acetylenes are able to displace ethylene from bridging or terminal 1,2-dithiolate ligands[225,341] to produce the 1,2-dithiolenes. In these reactions the sulfur rather than the metal sites of the cluster are reactive toward these small unsaturated molecules. Clearly, for nitrogenase, where we do not know the mode of binding, sulfur coordination might be a viable possibility. The $(Cp')_2Mo_2S_4$ systems that bind H_2 and C_2H_2, wherein bound C_2H_2 can be reduced to C_2H_4 and displaced by C_2H_2, are potential models for substrate reduction by nitrogenase.[225,342]

The versatility of transition-metal sulfur systems is further illustrated by the observation that activated acetylene can insert into a metal-sulfur bond in $Mo_2O_2S_2(S_2)_2^{2-}$, forming a vinyl-disulfide-chelating ligand

Figure 7.39 shows three possible modes of C_2H_2 binding, each of which is possible for the nitrogenase system.

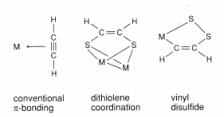


Figure 7.39 - Possible modes of acetylene binding to metal-sulfur sites.

It has recently been suggested[343] that the presence of a dihydrogen complex is required for H_2 to be displaced by N_2 to form a dinitrogen complex. This reaction would explain the required stoichiometry of N_2 reduction and H_2 evolution. Such an explanation had been suggested previously with dihydride complexes acting as the N_2-binding and N_2-displacing site.[182] Clearly, this new suggestion is an interesting embellishment of potential N_2/H_2 relationships.

At present, the activation process that is at work in the enzyme is unknown. We need greater structural definition of the active site, which should be forthcoming through the continued application of sophisticated diffraction and spectroscopic probes. Diffraction alone, however, will be incapable of locating protons and possibly other low-molecular-weight ligands. Therefore, spectroscopic probes such as ENDOR[10] and ESEEM,[277-279,344] which are based on EPR spectroscopy, and x-ray-based techniques, such as EXAFS and XANES, will remain crucial in elucidating mechanistically significant structural details.