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Recent Developments in Homogeneous Dinitrogen Reduction by Molybdenum and Iron

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Abstract

The reduction of gaseous nitrogen (N_2) is a challenge for industrial, biological and synthetic chemists, who want to understand the formation of ammonia (NH_3) for agriculture and also want to form N-C and N-Si bonds for fine chemical synthesis. The iron-molybdenum active site of nitrogenase has inspired chemists to explore the ability of iron and molybdenum complexes to bring about transformations related to N_2 reduction. This area of research has gained significant momentum, and the last two years have witnessed a number of significant advances in synthetic Fe- N_2 and Mo- N_2 chemistry. In addition, the identities of all atoms in the iron-molybdenum cofactor of nitrogenase have finally been elucidated, and the discovery of a carbide has generated new questions and targets for coordination chemists. This Perspective summarizes the recent work on iron and molybdenum complexes, and highlights the opportunities for continued research.

Dinitrogen (N_2) is one of the most plentiful molecules around us, but ironically it is one of the most difficult to use for chemical processes. Its thermodynamic stability and nonpolar nature make it unreactive, and it is often used as an “inert gas.” However, since the nitrogen atoms from N_2 are essential for agriculture, chemical reactions that transform N_2 into more versatile molecules are necessary. Ammonia (NH_3) is the most common product of these reduction reactions, and the synthesis of value-added organic molecules from N_2 would also be worthwhile. In addition to these practical targets, chemists are also motivated by the challenge of activating the strong N-N triple bond through controllable and/or catalytic reactions. For these reasons, there is a long history of research in N_2 reduction by transition-metal complexes.^{1,2,3}

This article examines recent research progress on molybdenum and iron complexes that are capable of N_2 reduction. Because of space limitations, and to avoid treading the same ground as earlier reviews,^{4,5} we will focus on N_2 -reducing complexes of Mo and Fe reported in the last two years. Mo and Fe have received the most attention because of their presence in Mo-dependent nitrogenase, for which the active site is a cluster called the iron-molybdenum cofactor or FeMoco. Chemists’ understanding of Mo-dependent nitrogenase itself has also benefitted from recent revelations, and these will be described near the end of the Perspective. We refer the reader to earlier reviews (and the papers cited therein) for discussions of N_2 reduction chemistry with a broader coverage of synthetic chemistry with other metals.^{1,2,3}

Dinitrogen reduction and functionalization at Mo

Historically, molybdenum has been the most successful metal for homogeneous N_2 reduction reactions. In prominent examples, Chatt described stoichiometric N_2 reduction reactions with protons,^{6,7} Shilov and Schrock reported catalytic reductions to ammonia,^{8,9}

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and Shiina, Hidai, and Mizobe reported catalytic reduction of N_2 to silylamines and organonitrogen compounds.^{3,10} Research reported in the last two years has built upon these seminal discoveries.

One strategy, pioneered by Shiina¹⁰ and further developed by Hidai,¹¹ is to functionalise dinitrogen using a silyl chloride and an alkali metal reductant. Nishibayashi recently described research that evaluated the idea that electron flow into the catalytic metal could be facilitated by the one-electron redox couple in ferrocene.¹² A Mo- N_2 complex featuring two depf (depf = 1,1'-bis(diethylphosphino)ferrocene) ligands, *trans*-[Mo(N_2)₂(depf)₂], catalysed the transformation of N_2 into tris(trimethylsilyl)amine [N(SiMe₃)₃] in the presence of chlorotrimethylsilane (Me₃SiCl) and Na metal as a stoichiometric reductant (Figure 1a). This reaction gave up to 226 equivalents of N(SiMe₃)₃ per mole of Mo catalyst, much more than the catalyst lacking the ferrocene substituents.¹¹ The authors also found that reaction of Mo(N_2)₂(depf)₂ with Me₃SiOTf (OTf = trifluoromethanesulfonate) produced the potential intermediate Mo(depfp)₂(OTf)(NNSiMe₃). On the basis of DFT calculations, the authors proposed the formation of Me₃Si• radicals, which would react with the Mo(N_2)₂(depf)₂ catalyst to form Mo(depfp)₂(NNSiMe₃), followed by a series of additional radical reactions to produce N(SiMe₃)₃. Additional studies are necessary to gain experimental support for this mechanism. Though the ferrocenes were introduced as a potential electron-transfer pathway, there was no clear evidence that the redox activity of the ferrocene substituents played a role in the catalytic efficiency. Nevertheless, these results serve as a strong motivation to incorporate redox-active ligands into other N_2 reduction systems in the future.

A series of other reports have utilised tridentate pincer ligands for controlling the reactivity of Mo. One used the molybdenum(0) complex [PNP]Mo(PMe₂Ph)(N_2)₂, where PNP = 2,6-bis(di-*tert*-butylphosphinomethyl)pyridine.¹³ When treated with an excess of H₂SO₄ at room temperature, it produced significant amounts of NH₃ (1.4 equiv per Mo), as shown in Figure 1b. By comparison, the previously reported *trans*-[Mo(N_2)₂(triphos)(PPh₃)], where triphos = PhP(CH₂CH₂PPh₂)₂, reacted with HBr to provide 0.9 equiv of NH₃,¹⁴ and *cis*-[M(N_2)₂(PMe₂Ph)₄] provided 0.7 (M = Mo) or 2.0 (M = W) equiv of NH₃ upon treatment with H₂SO₄.⁶ In contrast, the W- N_2 complex [PNP]W(PMe₂Ph)(N_2)₂ produced hydrazine (0.6 equiv) as the major product upon treatment with H₂SO₄ under the same reaction conditions as the Mo- N_2 analogue (Figure 1b).¹³ The different N_2 reduction products for Mo vs. W suggest that there are different relative rates for reduction vs. protonation of a hydrazido intermediate. This is an interesting difference from earlier systems where the W complex was postulated to be more efficient than Mo because of its more electron-rich metal center.¹⁴ Better understanding of the mechanisms is expected to elucidate how the product distribution may be controlled.

These stoichiometric reactions were extended to catalytic N_2 reduction, using the related bimetallic molybdenum(0)- N_2 species {[PNP]Mo(N_2)₂}₂(μ- N_2) (Figure 1c).¹⁵ This complex catalysed the conversion of N_2 to ammonia under one atmosphere of N_2 at room temperature using conditions similar to those of Schrock,⁸ with lutidinium triflate as the proton source and cobaltocene as a stoichiometric reductant. This reaction produced 12 moles of ammonia per mole of Mo.

In the proposed mechanism of ammonia formation, the bimetallic molybdenum species first breaks apart to form a monometallic tris(dinitrogen) species, which then undergoes a series of proton and electron transfers to convert the bound N_2 into ammonia. This mechanistic proposal is consistent with the observed decrease in catalyst activity toward ammonia formation with the use of smaller PNP ligands,¹⁶ because the greater steric pressure of the larger PNP ligands is expected to favour formation of the reactive monometallic tris(dinitrogen) species. Interestingly, the monometallic species [PNP]Mo(PMe₂Ph)(N_2)₂,

discussed in the previous paragraph, did not catalytically reduce N_2 under the same reaction conditions. A bimetallic carbonyl analogue, $\{[PNP]Mo(CO)_2\}_2(\mu-N_2)$, was also ineffective for catalytic ammonia production. These results suggest that incorporation of strongly-binding monodentate ligands reduces the reactivity of the complex toward ammonia formation. The number of turnovers from the PNP-supported Mo complex compares favourably to the results from Schrock's Mo complex supported by a tetradentate triamidoamine ligand.⁸ Therefore, the new work shows that both triamidoamine and PNP are each appropriate scaffolds for N_2 reduction by protons and electrons, despite the different coordinating geometries.

In another ligand variation, Schrock and co-workers reported the Mo chemistry of a tridentate POCOP ligand framework (POCOP = $C_6H_3-1,3-[OP(t-Bu)_2]_2$) that replaced the coordinating nitrogen in the above PNP ligand with an anionic carbon, and had oxygens in place of the methylene bridges (Figure 1d).¹⁷ In the POCOP system, reduction of N_2 by a transient molybdenum(II) species gave a terminal nitride complex from cleavage of N_2 . However, this nitride complex was not protonated at nitrogen. Accordingly, this POCOP-Mo system was not capable of catalytic N_2 reduction. It is possible that the "dead-end" nitride complex was unsuitable as a Brønsted base, that the presence of an iodide ligand inhibited the catalytic reaction (by analogy to the CO and phosphine inhibition discussed above), or that ligand flexibility makes possible an undesired side reaction.

Cummins has made a recent contribution that builds upon his Mo-mediated reduction of N_2 to nitride,¹⁸ by demonstrating the conversion of this nitride into a cyanide group.¹⁹ The initial C–N bond was formed by attack of the nitride on $MeOCH_2I$, which forms a cationic $[N(t-Bu)Ar]_3Mo(NCH_2OMe)^+$ species, followed by deprotonation to give a methoxyketimide $[N(t-Bu)Ar]_3Mo[NC(H)OMe]$. Addition of $SnCl_2$ and excess Me_2NSiMe_3 gave the cyanide product $[N(t-Bu)Ar]_3Mo(CN)$. After this impressive demonstration of the ability to build CN^- from N_2 stoichiometrically, the next challenge is to produce this C–N bond catalytically.

Dinitrogen reduction and functionalization at Fe

Until 2011, there were no examples of complete stoichiometric N_2 reduction by Fe complexes.^{4,5} Nevertheless, researchers have studied N-containing Fe species that are part of *hypothetical* cycles for N_2 reduction at Fe.²⁰ These hypothetical cycles are modeled after Mo chemistry, and typically involve terminal nitride complexes of iron (even though no terminal nitrides have come from direct cleavage of dinitrogen yet in iron chemistry). In the most thoroughly studied example, Smith has created a terminal iron(IV)-nitride complex that is supported by a tris(carbene)borate ligand (Figure 2a). Reaction of this Fe nitride species with excess TEMPO-H (1-hydroxy-2,2,6,6-tetramethylpiperidine) afforded ammonia in 74% yield.²¹ Consideration of the relevant redox potentials and pK_a values indicated that the initial N–H bond formation proceeded by direct H-atom transfer from TEMPO-H to the Fe nitride through proton-coupled electron transfer. In support of radical-transfer ability of the nitride, reaction of the iron(IV) nitride with $Ph_3C\cdot$ gave a new $NCPh_3$ ligand. C–N bond formation was also observed upon treatment of this Fe-nitride species with CO and with *tert*-butyl isocyanide (Figure 2a).²² These latter reactions indicate that the iron(IV) nitride can be electrophilic. Similarly, an iron(V)-nitride species reacts with water and cobaltocene to give ammonia, suggesting the formation of a Brønsted base *in situ*.²³ The active species in this ammonia formation is not the iron(IV)-nitride described above, because independent reactions show that it is inert to water. The reaction pathways that lead to N–H, N–C, and N–P bond formation in this system are clearly ripe for further study.

Other series of papers have described the interconversions of “nitrogenous” ligands consisting of nitrogen and hydrogen atoms, which are related to N_2 reduction chemistry. Tyler,²⁴ Field,²⁵ and Peters^{26,27} have reported diazene (N_2H_2), hydrazine (N_2H_4), and ammonia complexes of iron that lie along a hypothetical “alternating” reduction mechanism for N_2 reduction by Fe.²⁸ The essential displacement of NH_3 by N_2 on iron was demonstrated by Peters, in research where reduction of an Fe center in an $(SiP_3)Fe$ complex ($SiP_3 = Si(o-C_6H_4PR_2)_3$ with $R = Ph$ or $i-Pr$) improved its ability to π backbond, causing preferential binding of N_2 over NH_3 .²⁹ However, these systems still lacked a key precedent: demonstration that iron complexes can stoichiometrically cleave the N-N bond of N_2 . This goal was achieved and reported in two different papers in 2011, each of which used a novel strategy that suggests future research directions.

One strategy, explored by Peters, has been the use of a flexible chelating ligand, tris[2-(diisopropylphosphino)phenyl]borane (TPB) (Figure 2b), in which the B can be viewed as a zero-electron neutral ligand (electron pair donated from metal to boron), as a two-electron dianionic ligand (electron pair donated from boron to metal), or as a resonance structure between these two limiting forms. Below, we use “formal” oxidation states that assume a neutral borane, though it should be understood that the oxidation level of iron would be more positive if the boron were assigned a negative charge. Reduction of $(TPB)FeBr$ with 1 equivalent of Na-naphthalide provided the formally iron(0)-dinitrogen complex $(TPB)Fe(N_2)$ (Figure 2b), which had an $S = 1$ ground state.³⁰ Reduction with additional Na gave the anionic $S = 1/2$ complex $Na[(TPB)Fe(N_2)]$. The N-N stretching band in this formally iron(-I) compound was significantly lower than that in the neutral analogues as a result of stronger π -backbonding.

Reaction of $Na[(TPB)Fe(N_2)]$ with silyl chloride electrophiles produced new N-Si bonds in silyldiazene (N_2SiMe_3) and disilylhydrazine ($N_2[Me_2SiCH_2CH_2SiMe_2]$) products (Figure 2b).³¹ The former type of N-Si bond formation at Fe was preceded only in other recent work from Peters.²⁹ Formation of a disilylhydrazide ligand from M- N_2 complexes is known with $M = Mo$ and W ,³² but this new work was the first time this was observed in an Fe complex. Treatment of the disilylhydrazide complex with *tert*-butyl isocyanide caused substitution of the isocyanide for one phosphine of the TPB ligand. Upon standing at room temperature, the isocyanide compound spontaneously cleaved the N-N bond (Figure 2b): one N atom of N_2 was now part of a disilylamide ligand, with the other N atom attached to B and P atoms of the supporting ligand. Therefore, this reaction sequence led to complete cleavage of the N-N bond of N_2 , and the energetic cost was paid by formation of new N-Si, N-P, and N-B bonds. This metal-ligand cooperativity shows significant potential for forming new bonds to the N fragments remaining from N_2 cleavage, though the modification of the supporting ligand in the product is incompatible with expansion of this reaction into a catalytic N_2 reduction.

In a different strategy, the first example of an Fe-nitride complex derived from N_2 was reported recently by our research group.³³ Reduction of a β -diketiminato-supported iron(II) chloride complex with potassium-graphite (one molar equivalent of K per Fe) under an atmosphere of N_2 resulted in formation of an Fe bis(nitride) compound. This cluster contained four β -diketiminato Fe fragments with two bridging nitride ligands derived from N_2 (Figure 3). This six-electron redox reaction oxidised the four iron(I) sites to two iron(III) (the two Fe atoms bridging the nitride ligands) and two iron(II) (the remaining two Fe atoms). The K^+ ions in the product provided structural stabilisation of the bis(nitride) structure through cation π interactions. The use of multiple iron atoms together with potassium to cleave the N-N bond of nitrogen is reminiscent of the Mittasch catalyst for the Haber-Bosch process, which has a low-valent iron surface “promoted” with potassium additives. The structure of the Mittasch catalyst has surface and subsurface nitrides and

oxides embedded in a defect-rich surface, and cleaves N₂ to nitrides in the limiting step of the catalytic reaction.³⁴ Therefore, the molecular iron-nitride compound is significant because it gives chemists a structurally confirmed complex from N₂ cleavage by Fe and K ions.³⁵

This reaction also serves as an example of how changes in the size of the supporting ligands can greatly influence N₂ reactivity. Earlier work on closely related iron-diketimate complexes showed products in which the N-N bond was weakened and lengthened, but not cleaved.³⁶ In the earlier complexes, one iron atom bound to each end of the N₂ molecule, but the bulky ligands prevented approach of additional iron centers to the coordinated N₂. The use of smaller diketimate ligands may enable approach of more metals to the N₂ molecule, culminating in cooperative N-N bond cleavage. This hypothesis is supported by the fact that the product has the nitride remnants of N₂ bound directly to *three* iron atoms. Computational investigation (using simplified ligands) suggested that three diketimate-bound iron(I) centers, K⁺, and an additional electron can approach the N₂ molecule in a side-on/side-on/end-on geometry from which N-N cleavage is favourable.³⁷ These pieces of evidence fit together into an overall model where simultaneous attack of more iron atoms is beneficial for N₂ activation. The strategic reduction of ligand size to give side-on N₂ and N-N cleavage finds precedent in the work of Chirik on cyclopentadienyl-supported zirconium complexes that cleave N₂.³⁸

Treatment of the tetrairon bis(nitride) complex with an excess of anhydrous HCl produced ammonium chloride in 82% yield. This report marked the first example of high-yielding N₂ conversion to NH₃ with an Fe based system. However, the reaction is not catalytic, as the excess acid degrades the iron-containing products. Current work focuses on the use of other acids and acid stoichiometries, in order to better control this reaction and understand the intermediates.

The use of milder sources of H is another important goal in the conversion of N₂ to NH₃, because these are more conducive to eventual *catalytic* N₂ reduction at Fe. For example, the hydrogenation of a ruthenium nitrido complex with H₂ was recently described.³⁹ In the diketimate-iron chemistry, it was reported that the bis(nitrido)tetrairon complex reacted with excess H₂ to give a diiron(II) bis(μ -hydride) complex and a 40% yield of ammonia.³³ Though the production of the hydride complex from H₂ has been reproducible, further experiments (not yet reported in detail) show that the ammonia observed in the H₂ reaction comes from H⁺ in the workup rather than from the reaction with H₂. Thus, addition of H₂ to this nitride complex does not actually produce NH₃, and the full reaction stoichiometry for the H₂ reaction is a topic of current inquiry.

Though catalytic reduction of N₂ to NH₃ by molecular iron complexes is not yet known, Nishibayashi has recently discovered the first example of catalytic N₂ reduction into N(SiMe₃)₃ by a solution iron complex.⁴⁰ The catalytic reduction was catalyzed by Fe(CO)₅ and by cyclopentadienyl-Fe compounds, in analogy to the Mo-catalyzed process in the previous section (Figure 1a).¹² In these reactions, mixtures of the catalysts with Me₃SiCl and Na metal under one atmosphere of N₂ provided up to 34 equivalents of N(SiMe₃)₃ per mole of Fe. A combination of computational and experimental results suggest that disilyliron(II) fragments may be the catalyst formed in situ. It is difficult to rule out the intermediacy of iron nanoparticles or small clusters in these catalytic reactions; note that the mercury drop test is ineffective for Fe because it is not amalgamated by mercury. Although further studies will be required to elucidate the mechanism involved in this process, analogy can be drawn to the well-characterized N-Si bond formation reported by Peters using well-defined Fe complexes, silyl chlorides, and Na (Figure 2b).³¹ Incorporation of other

supporting ligands may lead to Fe complexes where experimental characterization of the mechanism is feasible.

New structural revelations in the nitrogenase FeMoco

The most active nitrogenase enzyme has a catalytic cofactor called the iron-molybdenum cofactor (FeMoco). Chemists' view of the FeMoco for the last ten years has been informed by a 2002 crystal structure at 1.16 Å, which showed seven Fe, one Mo, nine bridging S, and a central atom whose identity was unknown.⁴¹ In 2011, simultaneous papers by DeBeer and by Einsle finally demonstrated that the central atom is a carbon (Figure 4).^{42,43} Three methods were used: (a) new crystallographic data to 1.0 Å resolution, (b) Electron Spin Echo Envelope Modulation (ESEEM) spectroscopy on fully ¹³C-labeled protein, which showed a signal due to coupling of the ¹³C nucleus to the ground-state spin, and (c) iron X-ray emission spectroscopy (XES), which gives valence-to-core emission signals that differ greatly depending on the atoms attached to iron. The identification as carbon was also supported in computations.⁴⁴

It is surprising to learn that the FeMoco is an organometallic cluster, and that a formal carbide (C⁴⁻) is present in a biological system. However, exceptional stability of an iron-carbide cluster should not be shocking, because solid-state iron carbide materials are strong (*e.g.* cast iron and steel). The source of the carbon atom in the FeMoco is S-adenosylmethionine (SAM), as shown by ¹⁴C tracer studies by Ribbe.⁴⁵ The insertion of carbon is brought about by the enzyme NifB, which reduces the sulfonium cation of SAM to transfer a methyl group to the nascent FeMoco. In the proposed mechanism, abstraction of another hydrogen atom from the methyl group forms an alkylidene intermediate, eventually culminating in a carbide product. In addition to the pressing mechanistic questions, the novel intermediates postulated in the FeMoco biosynthesis pose an added challenge to the inorganic chemistry community. In particular, chemists have never prepared any iron-sulfide cluster containing a metal-bound alkyl, alkylidene, alkylidyne, or carbide.

There are numerous other targets for synthetic chemists that would also help to understand the formation, structure, stability, and mechanism of the FeMoco. For example, no synthetic iron-sulfide compound has ever been observed to bind or reduce N₂. Another active area of research will continue to address synthetic compounds that demonstrate fundamental mechanisms through which H can be added and removed from iron-bound carbon and nitrogen atoms. For example, a very recent report described the interconversion of NH₂ and NH₃ groups on a tris(phosphino)borane-supported iron complex.⁴⁶ These studies are likely to assist in the growing understanding of N₂ reduction intermediates in iron-molybdenum nitrogenase.⁴⁷

The future of iron and molybdenum dinitrogen chemistry

In addition to spectacular examples of new reactions, new mechanisms, and new bonding modes, these new research papers point toward the next series of targets for chemists interested in N₂ reduction by Mo and Fe. In Mo chemistry, catalytic reduction of N₂ to NH₃ has been achieved, although the number of turnovers is limited. Therefore, the main goals in this area should be to increase the efficiency of this process, and to extend the catalytic chemistry to the formation of more valuable nitrogen-containing products. In Fe chemistry, one of the key goals is to find well-characterised molecular complexes that catalytically reduce N₂. Considering that iron is used in both surface and biological N₂ reduction, coordination chemists should also seek relevant supporting ligation on the Fe atom, including nitrides, oxides, and potassium (which are present in the technical Haber-Bosch

catalyst) and also carbide and sulfide ligation (which are present in the FeMoco of nitrogenase).

Much of the recent work on N_2 reduction has focused on the production of NH_3 . Although it is sometimes claimed that a homogeneous route for catalytic ammonia synthesis would be preferable to the high-temperature Haber-Bosch process, the presence of a solvent would create separation problems, and current Haber-Bosch technology already has an impressive 70% energy efficiency.³⁴ Biocatalytic N_2 reduction based on nitrogenase seems intuitively appealing because of the lower temperature and pressure, but is unattractive on a large scale because nitrogenase is not energy-efficient, hydrolyzing at least 16 molecules of ATP per molecule of N_2 reduced.⁴⁸ Thus, the promise of small-molecule or enzymatic catalysts for large-scale ammonia production is limited. Rather, the primary impact of synthetic complexes that reduce N_2 to ammonia is that they provide well-characterised structures and systematic studies that teach chemists about the fundamental mechanisms of N_2 reduction, and about analogies to enzyme and surface catalysts where the atomic-level mechanisms remain unknown. Additionally, chemists should strive to expand the range of products that can be derived from coordinated N_2 . In early transition metal chemistry, stoichiometric N_2 functionalisation now includes a range of N-C bond formation reactions, particularly through discoveries by Fryzuk⁴⁹ and Chirik.^{50,51,52,53,54,55,56} Thus, a current challenge is to make these N-C bond forming reactions catalytic, possibly by using middle (Mo) and late (Fe) transition metals like those described above. Because these reactions can construct value-added chemical compounds, there is significantly more promise for commercialization for fine chemicals than for ammonia synthesis.

How do the recent discoveries guide future work in coordination chemistry? One emerging theme is the importance of the supporting ligand. Comparison of the PNP vs. POCOP chemistry of Mo, and of the SiP₃ and TBP ligands of Fe, highlights the major influence that the supporting ligand can exert through changing a coordinating atom and/or changing the charge.

The spin state and coordination number of the metal are other important factors that differentiate many of the above compounds, and it is important to systematically understand their influences. There are not yet clear general trends that enable chemists to guide the choice of supporting ligands; this may be due to the multitude of possible rate- and turnover-limiting steps, and the relative rates of decomposition pathways are also likely to be important. Therefore, mechanistic studies are urgently needed. A second emerging theme is that cooperative attack on N_2 by multiple metals may be important; in these cases, steric effects may have a negative influence by preventing multiple metals from simultaneously approaching N_2 . However, other systems use monometallic M- N_2 chemistry, and in these cases extremely bulky ligands are indispensable. A third emerging theme is alkali metal binding: in both the TBP and diketiminate complexes of Fe that cleave N_2 , key intermediates have side-on interactions of N_2 with a sodium or potassium ion. The alkali metal cations can stabilise reduced N_2 species through Coulomb attractions, and may enforce key transition-state geometries for control over regiochemistry. Thus, there is a compelling case for incorporating alkali metal components into future molecular N_2 reduction systems. Overall, the rapid progress in both Mo and Fe chemistry suggests that the future is bright for transition-metal catalyzed N_2 reduction.

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References

1. Holland, PL. Nitrogen fixation. In: McCleverty, J.; Meyer, TJ., editors. *Comprehensive Coordination Chemistry II*. Vol. 8. Elsevier; 2004. p. 569-599.
2. MacKay BA, Fryzuk MD. Dinitrogen coordination chemistry: on the biomimetic borderlands. *Chem Rev*. 2004; 104:385-401. [PubMed: 14871129]
3. Hidai M, Mizobe Y. Recent advances in the chemistry of dinitrogen complexes. *Chem Rev*. 1995; 95:1115-1133.
4. Hazari N. Homogeneous iron complexes for the conversion of dinitrogen into ammonia and hydrazine. *Chem Soc Rev*. 2010; 39:4044-4056. [PubMed: 20571678]
5. Crossland JL, Tyler DR. Iron-dinitrogen coordination chemistry: dinitrogen activation and reactivity. *Coord Chem Rev*. 2010; 254:1883-1894.
6. Chatt J, Pearman AJ, Richards RL. Reduction of monocoordinated molecular nitrogen to ammonia in a protic environment. *Nature*. 1975; 253:39-40.
7. Chatt J, Pearman AJ, Richards RL. Conversion of dinitrogen in its molybdenum and tungsten complexes into ammonia and possible relevance to the nitrogenase reaction. *J Chem Soc, Dalton Trans*. 1977:1852-1860.
8. Denisov NT, Shuvalov VF, Shuvalova NI, Shilova AK, Shilov AE. Modelling of the biological fixation of nitrogen. Catalytic reduction of nitrogen in protonic media. *Dokl Akad Nauk SSSR*. 1970; 195:879-881.
9. Yandulov DV, Schrock RR. Catalytic reduction of dinitrogen to ammonia at a single molybdenum center. *Science*. 2003; 301:76-78. [PubMed: 12843387]
10. Shiina K. Reductive silylation of molecular nitrogen via fixation to tris(trialkylsilyl)amine. *J Am Chem Soc*. 1972; 94:9266-9267.
11. Komori K, Oshita H, Mizobe Y, Hidai M. Catalytic conversion of molecular nitrogen into silylamines using molybdenum and tungsten dinitrogen complexes. *J Am Chem Soc*. 1989; 111:1939-1940.
12. Tanaka H, et al. Molybdenum-catalyzed transformation of molecular dinitrogen into silylamine: experimental and DFT study on the remarkable role of ferrocenyldiphosphine ligands. *J Am Chem Soc*. 2011; 133:3498-3506. [PubMed: 21341772]
13. Arashiba K, et al. Synthesis and protonation of molybdenum- and tungsten-dinitrogen complexes bearing PNP-type pincer ligands. *Organometallics*. 2012; 31:2035-2041.
14. Baumann JA, et al. Formation of ammonia and hydrazine from the reactions of acids with bis(dinitrogen) complexes of molybdenum. *Inorg Chem*. 1985; 24:3568-3578.
15. Arashiba K, Miyake Y, Nishibayashi Y. A molybdenum complex bearing PNP-type pincer ligands leads to the catalytic reduction of dinitrogen into ammonia. *Nature Chem*. 2011; 3:120-125. [PubMed: 21258384]
16. Konishita E, et al. Synthesis and catalytic activity of molybdenum-dinitrogen complexes bearing unsymmetric PNP-type pincer ligands. *Organometallics*. 2012; 31:8437-8443.
17. Hebden TJ, Schrock RR, Takase MK, Muller P. Cleavage of dinitrogen to yield a (t-BuPOCOP)molybdenum nitride. *Chem Commun*. 2012; 48:1851-1853.
18. Laplaza CE, Cummins CC. Dinitrogen cleavage by a three-coordinate molybdenum(III) complex. *Science*. 1995; 268:861-863. [PubMed: 17792182]
19. Curley JJ, Cozzolino AF, Cummins CC. Nitrogen fixation to cyanide at a molybdenum center. *Dalton Trans*. 2011; 40:2429-2432. [PubMed: 21293816]
20. Peters, JC.; Mehn, MP. Bio-organometallic approaches to nitrogen fixation chemistry. In: Tolman, WB., editor. *Activation of Small Molecules*. VCH; 2006. p. 81-119.
21. Scepaniak JJ, Young JA, Bontchev RP, Smith JM. Formation of ammonia from an iron nitrido complex. *Angew Chem, Int Ed*. 2009; 48:3158-3160.
22. Scepaniak JJ, Bontchev RP, Johnson DL, Smith JM. Snapshots of complete nitrogen atom transfer from an iron(IV) nitrido complex. *Angew Chem, Int Ed*. 2011; 50:6630-6633.
23. Scepaniak JJ, et al. Synthesis, structure, and reactivity of an iron(V) nitride. *Science*. 2011; 331:1049-1052. [PubMed: 21350172]

24. Crossland JL, Balesdent CG, Tyler DR. Coordination of a complete series of N₂ reduction intermediates to an iron phosphine scaffold. *Inorg Chem.* 2012; 51:439–445. [PubMed: 22017491]
25. Field LD, Li HL, Magill AM. Base-mediated conversion of hydrazine to diazene and dinitrogen at an iron center. *Inorg Chem.* 2008; 48:5–7. [PubMed: 19046077]
26. Saouma CT, Muller P, Peters JC. Characterization of structurally unusual diiron N_xH_y complexes. *J Am Chem Soc.* 2009; 131:10358–10359. [PubMed: 19722612]
27. Saouma CT, Kinney RA, Hoffman BM, Peters JC. Transformation of an [Fe(η^2 -N₂H₃)]⁺ species to π -delocalized [Fe₂(μ -N₂H₂)]^{2+/-} complexes. *Angew Chem, Int Ed.* 2011; 50:3446–3449.
28. Hoffman BM, Dean DR, Seefeldt LC. Climbing nitrogenase: toward a mechanism of enzymatic nitrogen fixation. *Acc Chem Res.* 2009; 42:609–619. [PubMed: 19267458]
29. Lee Y, Mankad NP, Peters JC. Triggering N₂ uptake via redox-induced expulsion of coordinated NH₃ and N₂ silylation at trigonal bipyramidal iron. *Nature Chem.* 2010; 2:558–565. [PubMed: 20571574]
30. Moret ME, Peters JC. Terminal iron dinitrogen and iron imide complexes supported by a tris(phosphino)borane ligand. *Angew Chem, Int Ed.* 2011; 50:2063–2067.
31. Moret ME, Peters JC. N₂ functionalization at iron metallaboratranes. *J Am Chem Soc.* 2011; 133:18118–18121. [PubMed: 22008018]
32. Oshita H, Mizobe Y, Hidai M. Novel disilylation of a dinitrogen ligand. *Organometallics.* 1992; 11:4116–4123.
33. Rodriguez MM, Bill E, Brennessel WW, Holland PL. N₂ Reduction and hydrogenation to ammonia by a molecular iron-potassium complex. *Science.* 2011; 334:780–783. [PubMed: 22076372]
34. Schlögl, R. *Handbook of Heterogeneous Catalysis.* 2. Vol. 5. Wiley-VCH; 2008. Ammonia synthesis; p. 2501-2575.
35. Mortensen JJ, Hansen LB, Hammer B, Norskov JK. Nitrogen adsorption and dissociation on Fe(111). *J Catal.* 1999; 182:479–488.
36. Smith JM, et al. Studies of low-coordinate iron dinitrogen complexes. *J Am Chem Soc.* 2006; 128:756–769. [PubMed: 16417365]
37. Figg TM, Holland PL, Cundari TR. Cooperativity between low-valent iron and potassium promoters in dinitrogen fixation. *Inorg Chem.* 2012; 51:7546–7550. [PubMed: 22734966]
38. Pool JA, Lobkovsky E, Chirik PJ. Hydrogenation and cleavage of dinitrogen to ammonia with a zirconium complex. *Nature.* 2004; 427:527–530. [PubMed: 14765191]
39. Askevold B, et al. Ammonia formation by metal–ligand cooperative hydrogenolysis of a nitrido ligand. *Nature Chem.* 2011; 3:532–537. [PubMed: 21697873]
40. Yuki M, et al. Iron-catalyzed transformation of molecular dinitrogen into silylamine under ambient conditions. *Nat Commun.* 2012; 3:1254.10.1038/ncomms2264 [PubMed: 23212383]
41. Einsle O, et al. Nitrogenase MoFe-protein at 1.16 Å resolution: a central ligand in the FeMo-cofactor. *Science.* 2002; 297:1696–1700. [PubMed: 12215645]
42. Spatzal T, et al. Evidence for interstitial carbon in nitrogenase FeMo cofactor. *Science.* 2011; 334:940. [PubMed: 22096190]
43. Lancaster KM, et al. X-ray emission spectroscopy evidences a central carbon in the nitrogenase iron-molybdenum cofactor. *Science.* 2011; 334:974–977. [PubMed: 22096198]
44. Harris TV, Szilagyi RK. Comparative assessment of the composition and charge state of nitrogenase FeMo-cofactor. *Inorg Chem.* 2011; 50:4811–4824. [PubMed: 21545160]
45. Wiig JA, Hu Y, Lee CC, Ribbe MW. Radical SAM-dependent carbon insertion into the nitrogenase M-cluster. *Science.* 2012; 337:1672–1675. [PubMed: 23019652]
46. Anderson JS, Moret ME, Peters JC. Conversion of Fe–NH₂ to Fe–N₂ with release of NH₃. *J Am Chem Soc.* 2013; 135:534–537. [PubMed: 23259776]
47. a) Lukoyanov D, et al. Unification of reaction pathway and kinetic scheme for N₂ reduction catalyzed by nitrogenase. *Proc Natl Acad Sci U S A.* 2012; 109:5583–5587. [PubMed: 22460797]
b Hoffman BM, Lukoyanov D, Dean DR, Seefeldt LC. Nitrogenase: a draft mechanism. *Acc Chem Res.* 2013; 46 in press. 10.1021/ar300267m

48. Burgess BK, Lowe DJ. Mechanism of molybdenum nitrogenase. *Chem Rev.* 1996; 96:2983–3011. [PubMed: 11848849]
49. Fryzuk MD. Side-on end-on bound dinitrogen: an activated bonding mode that facilitates functionalizing molecular nitrogen. *Acc Chem Res.* 2009; 42:127–133. [PubMed: 18803409]
50. Bernskoetter WH, Olmos AV, Pool JA, Lobkovsky E, Chirik PJ. N-C bond formation promoted by a hafnocene dinitrogen complex: comparison of zirconium and hafnium congeners. *J Am Chem Soc.* 2006; 128:10696–10697. [PubMed: 16910661]
51. Knobloch DJ, Toomey HE, Chirik PJ. Carboxylation of an ansa-zirconocene dinitrogen complex: regiospecific hydrazine synthesis from N₂ and CO₂. *J Am Chem Soc.* 2008; 130:4248–4249. [PubMed: 18327948]
52. Knobloch DJ, et al. Addition of methyl triflate to a hafnocene dinitrogen complex: stepwise N₂ methylation and conversion to a hafnocene hydrazonato compound. *J Am Chem Soc.* 2009; 131:14903–14912. [PubMed: 19785422]
53. Knobloch DJ, Lobkovsky E, Chirik PJ. Carbon monoxide-induced dinitrogen cleavage with group 4 metallocenes: reaction scope and coupling to N-H bond formation and CO deoxygenation. *J Am Chem Soc.* 2010; 132:10553–10564. [PubMed: 20662528]
54. Knobloch DJ, Lobkovsky E, Chirik PJ. Dinitrogen cleavage and functionalization by carbon monoxide promoted by a hafnium complex. *Nature Chem.* 2010; 2:30–35. [PubMed: 21124377]
55. Knobloch DJ, Semproni SP, Lobkovsky E, Chirik PJ. Studies into the mechanism of CO-induced N₂ cleavage promoted by an ansa-hafnocene complex and C-C bond formation from an observed intermediate. *J Am Chem Soc.* 2012; 134:3377–3386. [PubMed: 22324370]
56. Semproni SP, Milsmann C, Chirik PJ. Structure and reactivity of a hafnocene μ -nitrido prepared from dinitrogen cleavage. *Angew Chem, Int Ed.* 2012; 51:5213–5216.

Figure 1.

Key developments in molybdenum- N_2 chemistry. (a) Catalytic conversion of dinitrogen to tris(trimethylsilyl)amine by a depf-supported Mo complex (right). (b) Synthesis and stoichiometric reactions of PNP-supported Mo and W dinitrogen compounds. (c) Catalytic formation of ammonia with $\{[\text{PNP}]\text{Mo}(\text{N}_2)_2\}_2(\mu\text{-N}_2)$ as catalyst. (d) Stoichiometric N_2 reduction by a POCOP-supported Mo complex.

Figure 2.

Recent monometallic iron-based transformations of N₂ or nitride. (a) Functionalization of terminal iron-nitride complexes. The reactions with triphenylphosphine (PPh₃), carbon monoxide (CO), and *tert*-butyl isocyanide (CN^tBu) demonstrate electrophilic reactivity at N, while the reaction with TEMPO-H on the right demonstrates abstraction of a hydrogen atom. (b) Dinitrogen activation and cleavage in a tris(phosphino)borate-iron system. The series of reactions along the top show addition of an electrophilic silyl group to coordinated N₂. Addition of two silyl groups in the bottom pathway gives a product that leads to eventual N-N bond cleavage.

Figure 3. Reduction of a diiron(II) dimer (using one equivalent of potassium graphite per iron atom) gives spontaneous cleavage of the N-N bond to form a bis(nitride) product. The nitride complex may be treated with acid to give a high yield of ammonia.

Figure 4.

Spectroscopic, crystallographic, and ¹⁴C tracer studies recently elucidated the final details of the atomic structure of the FeMoco of molybdenum-dependent nitrogenase, demonstrating that the cluster has a carbide core. This carbide is hypervalent, and has bonding interactions with six of the seven iron atoms in the cluster.