DOI: 10.1021/ic100856n

Inorganic Chemistry
Article

Synthesis of DiamidoPyrrolyl Molybdenum Complexes Relevant to Reduction of Dinitrogen to Ammonia

J. M. Chin, R. R. Schrock,* and P. Müller

Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received April 30, 2010

A potentially useful trianionic ligand for the reduction of dinitrogen catalytically by molybdenum complexes is one in which one of the arms in a $[(RNCH_2CH_2)_3N]^{3-}$ ligand is replaced by a 2-mesitylpyrrolyl-α-methyl arm, that is, $[(RNCH_2CH_2)_2NCH_2(2\text{-MesitylPyrrolyl})]^{3-}$ (R = C_6F_5, 3,5-$Me_2C_6H_3$, or 3,5-*t*-$Bu_2C_6H_3$). Compounds have been prepared that contain the ligand in which R = C_6F_5 ($[(C_6F_5N)_2Pyr]^{3-}$); they include $[(C_6F_5N)_2Pyr]Mo(NMe_2)$, $[(C_6F_5N)_2Pyr]MoCl$, $[(C_6F_5N)_2Pyr]MoOTf$, and $[(C_6F_5N)_2Pyr]MoN$. Compounds that contain the ligand in which R = 3,5-*t*-$Bu_2C_6H_3$ ($[(Ar^{t\text{-}Bu}N)_2Pyr]^{3-}$) include $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(15\text{-crown-}5)$, $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}[NBu_4]$, $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ (ν_{NN} = 2012 cm^{-1} in C_6D_6), $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$, and $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$. X-ray studies are reported for $[(C_6F_5N)_2Pyr]Mo(NMe_2)$, $[(C_6F_5N)_2Pyr]MoCl$, and $[(Ar^{t\text{-}Bu}N)_2Pyr]MoN$. The $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)^{0/-}$ reversible couple is found at −1.96 V (in PhF versus $Cp_2Fe^{+/0}$), but the $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)^{+/0}$ couple is irreversible. Reduction of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ under Ar at approximately −1.68 V at a scan rate of 900 mV/s is not reversible. Ammonia in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)$ can be substituted for dinitrogen in about 2 h if 10 equiv of BPh_3 are present to trap the ammonia that is released. $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo{-}N{=}NH$ is a key intermediate in the proposed catalytic reduction of dinitrogen that could not be prepared. Dinitrogen exchange studies in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ suggest that steric hindrance by the ligand may be insufficient to protect decomposition of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo{-}N{=}NH$ through a variety of pathways. Three attempts to reduce dinitrogen catalytically with $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N)$ as a "catalyst" yielded an average of 1.02 ± 0.12 equiv of NH_3.

Introduction

Nitrogenase enzymes (in algae and bacteria) convert dinitrogen to ammonia, but despite intensive study, the mechanism of this conversion is not well understood.[1] Discovery of the first transition metal dinitrogen complex, $[Ru(NH_3)_5(N_2)]^{+}$,[2] inspired syntheses of other transition metal dinitrogen complexes in the hope that an abiological method of reducing dinitrogen under mild conditions could be devised, one that might eventually compete with or replace the Haber−Bosch process.[3] Work concerning dinitrogen functionalization continues today on several fronts.[4−7]

Only two systems are known in which dinitrogen can be reduced catalytically to ammonia under mild conditions. The first, reported by Shilov,[3h] requires molybdenum and a

*To whom correspondence should be addressed. E-mail: rrs@mit.edu.

(1) (a) Burgess, B. K. *Chem. Rev.* **1990**, *90*, 1377. (b) Burgess, B. K.; Lowe, D. *J. Chem. Rev.* **1996**, *96*, 2983. (c) Rees, D. C.; Howard, J. B. *Curr. Opin. Chem. Biol.* **2000**, *4*, 559. (d) Rees, D. C.; Chan, M. K.; Kim, J. *Adv. Inorg. Chem.* **1996**, *40*, 89. (e) Eady, R. R. *Chem. Rev.* **1996**, *96*, 3013. (f) Howard, J. B.; Rees, D. C. *Chem. Rev.* **1996**, *96*, 2965. (g) Kim, J.; Woo, D.; Rees, D. C. *Biochemistry* **1993**, *32*, 7104. (h) Kim, J.; Rees, D. C. *Nature* **1992**, *360*, 553. (i) Bolin, J. T.; Ronco, A. E.; Morgan, T. V.; Mortenson, L. E.; Xuong, L. E. *Proc. Natl. Acad. Sci.* **1993**, *90*, 1078. (j) Chen, J.; Christiansen, J.; Campobasso, N.; Bolin, J. T.; Tittsworth, R. C.; Hales, B. J.; Rehr, J. J.; Cramer, S. P. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1592. (k) Einsle, O.; Tezcan, F. A.; Andrade, S. L. A.; Schmid, B.; Yoshida, M.; Howard, J. B.; Rees, D. C. *Science* **2002**, *297*, 1696. (l) Hardy, R. W. F.; Bottomley, F.; Burns, R. C. *A Treatise on Dinitrogen Fixation*; Wiley-Interscience: New York, 1979. (m) Christiansen, J.; Dean, D. R.; Seefeldt, L. C. *Annu. Rev. Plant. Physiol. Plant. Mol. Biol.* **2001**, *52*, 269. (n) Dos Santos, P. C.; Igarashi, R. Y.; Lee, H.; Hoffman, B. M.; Seefeldt, L. C.; Dean, D. R. *Acc. Chem. Res.* **2005**, *38*, 208. (o) Dance, I. *Chem. Asian J.* **2007**, *2*, 936. (p) Kästner, J.; Blöchl, P. E. *J. Am. Chem. Soc.* **2007**, *129*, 2998.

(2) Allen, A. D.; Senoff, C. V. *J. Chem. Soc., Chem. Commun.* **1965**, 621.

(3) (a) Fryzuk, M. D.; Johnson, S. A. *Coord. Chem. Rev.* **2000**, *200−202*, 379. (b) Hidai, M.; Mizobe, Y. *Chem. Rev.* **1995**, *95*, 1115. (c) Hidai, M. *Coord. Chem. Rev.* **1999**, *185−186*, 99. (d) Chatt, J.; Dilworth, J. R.; Richards, R. L. *Chem. Rev.* **1978**, *78*, 589. (e) Richards, R. L. *Coord. Chem. Rev.* **1996**, *154*, 83. (f) Richards, R. L. *Pure Appl. Chem.* **1996**, *68*, 1521. (g) Bazhenova, T. A.; Shilov, A. E. *Coord. Chem. Rev.* **1995**, *144*, 69. (h) Shilov, A. E. *Russ. Chem. Bull. Int. Ed.* **2003**, *2*, 2555. (i) MacKay, B. A.; Fryzuk, M. D. *Chem. Rev.* **2004**, *104*, 385. (j) Gambarotta, S.; Scott, J. *Angew. Chem., Int. Ed.* **2004**, *43*, 5298. (k) Hidai, M.; Mizobe, Y. *Can. J. Chem.* **2005**, *83*, 358.

(4) (a) Knobloch, D. J.; Lobkovsky, E.; Chirik, P. J. *Nat. Chem.* **2010**, *2*, 30. (b) Hanna, T. E.; Lobkovsky, E.; Chirik, P. J. *Organometallics* **2009**, *28*, 4079. (c) Munha, R. F.; Veiros, L. F.; Duarte, M. T.; Fryzuk, M. D.; Martins, A. M. *Dalton Trans.* **2009**, 7494. (d) Kozak, C. M.; Mountford, P. *Angew. Chem., Int. Ed.* **2004**, *43*, 1186. (e) Fryzuk, M. D. *Acc. Chem. Res.* **2009**, *42*, 127. (f) Chirik, P. J. *Dalton Trans.* **2007**, 16.

(5) (a) Smith, J. M.; Lachicotte, R. J.; Holland, P. L. *J. Am. Chem. Soc.* **2003**, *125*, 15752. (b) Eckert, N. A.; Smith, J. M.; Lachicotte, R. J.; Holland, P. L. *Inorg. Chem.* **2004**, *43*, 3306. (c) Holland, P. L. *Can. J. Chem.* **2005**, *83*, 296. (d) Smith, J. M.; Sadique, A. R.; Cundari, T. R.; Rodgers, K. R.; Lukat-Rodgers, G.; Lachicotte, R. J.; Flaschenriem, C. J.; Vela, J.; Holland, P. L. *J. Am. Chem. Soc.* **2006**, *128*, 756. (e) Field, L. D.; Li, H. L.; Magill, A. M. *Inorg. Chem.* **2009**, *48*, 5. (f) Whited, M. T.; Mankad, N. P.; Lee, Y.; Oblad, P. F.; Peters, J. C. *Inorg. Chem.* **2009**, *48*, 2507. (g) Lee, Y.; Mankad, N. P.; Peters, J. C. *Nat. Chem.* **2010**, *2*, 558. (h) Crossland, J. L.; Balesdent, C. G.; Tyler, D. R. *Dalton Trans.* **2009**, 4420.

(6) (a) Laplaza, C. E.; Cummins, C. C. *Science* **1995**, *268*, 861. (b) Laplaza, C. E.; Johnson, M. J. A.; Peters, J. C.; Odom, A. L.; Kim, E.; Cummins, C. C.; George, G. N.; Pickering, I. J. *J. Am. Chem. Soc.* **1996**, *118*, 8623.

(7) (a) Mori, M. *J. Organomet. Chem.* **2004**, *689*, 4210. (b) Komori, K.; Oshita, H.; Mizobe, Y.; Hidai, M. *J. Am. Chem. Soc.* **1989**, *111*, 1939.

Published on Web 07/27/2010
© 2010 American Chemical Society

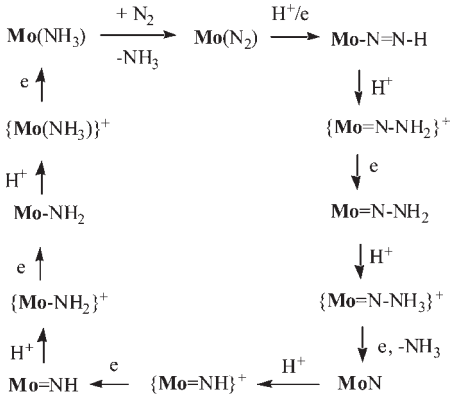


Figure 1. Proposed intermediates in the reduction of dinitrogen at a $[HIPTN_3N]Mo$ (Mo) center (HIPT = hexaisopropylterphenyl) through stepwise addition of protons and electrons.

strong reducing agent in methanol. Dinitrogen is reduced first to hydrazine, which is then disproportionated to dinitrogen and ammonia. A typical product is a 1:10 mixture of ammonia and hydrazine. The second catalytic process is selective for formation of ammonia.[8] Dinitrogen is reduced at room temperature (RT) and ambient pressure at a single Mo center protected by a sterically demanding, hexaisopropylterphenyl-substituted triamidoamine ligand, $[(3,5\text{-}(2,4,6\text{-i-}Pr_3C_6H_2)_2C_6H_3NCH_2CH_2N)_3N]^{3-}$ ($[HIPTN_3N]^{3-}$). Eight of the intermediates in the proposed reduction sequence (Figure 1) were prepared and characterized and several were employed for catalytic N_2 reduction. Slow addition of $CrCp^*_2$ ($Cp^* = \eta^5\text{-}C_5Me_5^-$) to a heptane solution of $[HIPTN_3N]Mo(N_2)$, $[HIPTN_3N]MoN$, $[HIPTN_3N]MoN{=}NH$, or $\{[HIPTN_3N]Mo(NH_3)\}^+$ containing sparingly soluble [2,6-lutidinium][BAr′] (Ar′ = 3,5-$(CF_3)_2C_6H_3$) led to catalytic reduction of dinitrogen to ammonia, with approximately 1 equiv of dihydrogen being formed per dinitrogen reduced. The maximum yield of ammonia is approximately 8 equiv (four turnovers).

Synthesis and investigation of several variations of the $[HIPTN_3N]^{3-}$ ligand system have shown that use of sterically less demanding ligands or more sterically demanding ligands (the hexa-*t*-butylterphenyl analogue) lead to a decrease in the efficiency of dinitrogen reduction, or even loss of catalytic activity entirely.[9] $[HIPTN_3N]Mo$ complexes currently are the most efficient catalysts. Analogous vanadium,[10] chromium,[11] and tungsten[12] systems showed no catalytic activity. Calculations have been carried out on the molybdenum catalyst system,[13] including density functional theory (DFT) calculations with the full ligand,[14] that support the proposed mechanism for dinitrogen reduction in the $[HIPTN_3N]Mo$ system.

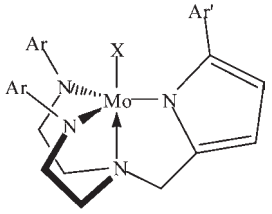


Figure 2. "Diamidopyrrolyl" complex.

One of the main reasons why dinitrogen reduction is limited to approximately four turnovers is that the $[HIPTN_3N]^{3-}$ ligand is protonated at an amido nitrogen and ultimately removed from the metal in the presence of reducing agent and acid.[8e,f] Replacing the substituted amido groups in the triamidoamine ligand by pyrrolyl (or pyrrolide) groups was the rationale for the synthesis of complexes that contain a tris(pyrrolyl-α-methyl)amine ligand.[15] However, replacing the three HIPT-substituted amido groups with three substituted pyrrolyl groups is too large a perturbation on the already sensitively electronically and sterically balanced $[HIPTN_3N]^{3-}$ ligand system; a significant problem proved to be binding the tris(pyrrolyl-α-methyl)-amine ligand to the metal in a tetradentate fashion. Therefore we turned to the construction of a variation in which one $ArNCH_2CH_2$ arm in the trianionic triamidoamine ligand is replaced by a pyrrolyl-α-methyl arm; a "diamidopyrrolyl" complex, as shown in Figure 2, became the target. The Ar′ group bound to the α carbon atom in the pyrrolyl (e.g., Ar′ = mesityl) should provide a significant amount of steric protection of a ligand in the apical coordination site. A pyrrolyl would seem less likely to be protonated than an amido nitrogen, and if the pyrrolyl *is* protonated, the proton is likely to add to an α or β carbon atom to yield a pyrrolenine bound to a cationic metal center, as has been shown recently for a cationic tungsten complex.[16] A pyrrolenine donor is likely to bind more strongly to a cationic metal center than the aniline formed upon protonation of an amido ligand. Consequently, protonation of a pyrrolyl ligand may yield a relatively stable cationic species. Therefore we felt that a catalyst that contains a diamidopyrrolyl ligand could turn out to be a more stable catalyst for dinitrogen reduction, assuming that all other requirements are met. We report here efforts to prepare complexes that contain diamidopyrrolyl ligands and that function as catalysts for reduction of dinitrogen to ammonia.

(8) (a) Yandulov, D. V.; Schrock, R. R. *J. Am. Chem. Soc.* **2002**, *124*, 6252. (b) Yandulov, D. V.; Schrock, R. R.; Rheingold, A. L.; Ceccarelli, C.; Davis, W. M. *Inorg. Chem.* **2003**, *42*, 796. (c) Yandulov, D. V.; Schrock, R. R. *Inorg. Chem.* **2005**, *44*, 1103. (d) Yandulov, D. V.; Schrock, R. R. *Science* **2003**, *301*, 76. (e) Schrock, R. R. *Angew. Chem., Int. Ed.* **2008**, *47*, 5512. (f) Schrock, R. R. *Acc. Chem. Res.* **2005**, *38*, 955.

(9) (a) Ritleng, V.; Yandulov, D. V.; Weare, W. W.; Schrock, R. R.; Hock, A. S.; Davis, W. M. *J. Am. Chem. Soc.* **2004**, *126*, 6150. (b) Weare, W. W.; Dai, X.; Byrnes, M. J.; Chin, J. M.; Schrock, R. R.; Müller, P. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103*, 17099. (c) Weare, W. W.; Schrock, R. R.; Hock, A. S.; Müller, P. *Inorg. Chem.* **2006**, *45*, 9185.

(10) Smythe, N. C.; Schrock, R. R.; Müller, P.; Weare, W. W. *Inorg. Chem.* **2006**, *45*, 9197.

(11) Smythe, N. C.; Schrock, R. R.; Müller, P.; Weare, W. W. *Inorg. Chem.* **2006**, *45*, 7111.

(12) Yandulov, D. V.; Schrock, R. R. *Can. J. Chem.* **2005**, *83*, 341.

(13) (a) Cao, Z.; Zhou, A.; Wan, H. L.; Zhang, Q. *Int. J. Quantum Chem.* **2005**, *103*, 344. (b) Le Guennic, B.; Kirchner, B.; Reiher, M. *Chem.—Eur. J.* **2005**, *11*, 7448. (c) Studt, F.; Tuczek, F. *Angew. Chem., Int. Ed.* **2005**, *44*, 5639. (d) Mersmann, K.; Horn, K. H.; Böres, N.; Lehnert, N.; Studt, F.; Paulat, F.; Peters, G.; Ivanovic-Burmazovic, I.; van Eldik, R.; Tuczek, F. *Inorg. Chem.* **2005**, *44*, 3031. (e) Khoroshun, D. V.; Musaev, D. G.; Morokuma, K. *Mol. Phys.* **2002**, *100*, 523. (f) Neese, F. *Angew. Chem., Int. Ed.* **2006**, *45*, 196. (g) Hölscher, M.; Leitner, W. *Eur. J. Inorg. Chem.* **2006**, 4407. (h) Magistrato, A.; Robertazzi, A.; Carloni, P. *J. Chem. Theory Comput.* **2007**, *3*, 1708. (i) Studt, F.; Tuczek, F. *J. Comput. Chem.* **2006**, *27*, 1278. (j) Stephan, G. C.; Sivasankar, C.; Studt, F.; Tuczek, F. *Chem.—Eur. J.* **2008**, *14*, 644.

(14) (a) Reiher, M.; Le Guennic, B.; Kirchner, B. *Inorg. Chem.* **2005**, *44*, 9640. (b) Schenk, S.; Le Guennic, B.; Kirchner, B.; Reiher, M. *Inorg. Chem.* **2008**, *47*, 3634. (c) Schenk, S.; Kirchner, B.; Reiher, M. *Chem.—Eur. J.* **2009**, *15*, 5073.

(15) Wampler, K. M.; Schrock, R. R. *Inorg. Chem.* **2007**, *46*, 8463.

(16) Kreickmann, T.; Arndt, S.; Schrock, R. R.; Müller, P. *Organometallics* **2007**, *26*, 5702.

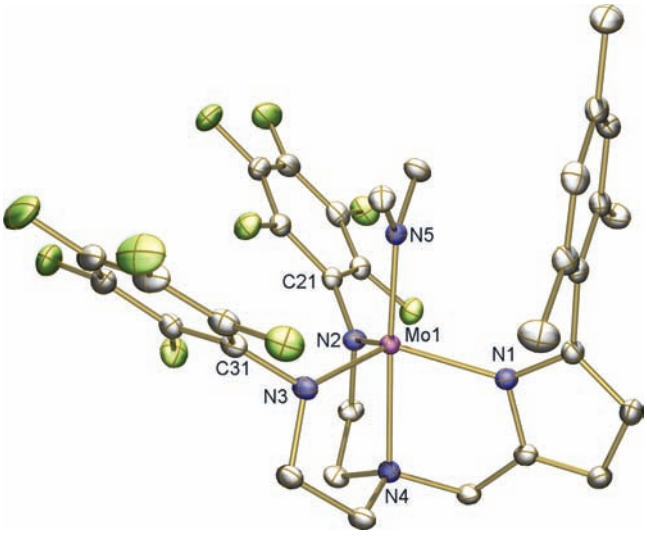
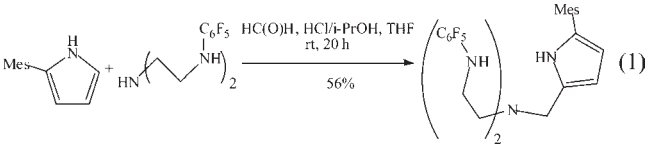


Figure 3. Thermal ellipsoid drawing (50% probability) of the solid state structure of $[(C_6F_5N)_2Pyr]Mo(NMe_2)$. H atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): N(5)−Mo(1) = 1.9383(12), Mo(1)−N(3) = 1.9738(12), Mo(1)−N(2) = 1.9885(12), Mo(1)−N(1) = 2.0807(12), Mo(1)−N(4) = 2.2630(12), C(21)−N(2)−Mo(1) = 129.36(10), C(31)−N(3)−Mo(1) = 128.3(3), N(1)−Mo(1)−N(4) = 77.26(5), N(2)−Mo(1)−N(4) = 78.61(5), N(3)−Mo(1)−N(4) = 77.51(5), N(5)−Mo(1)−N(4) = 176.92(5).

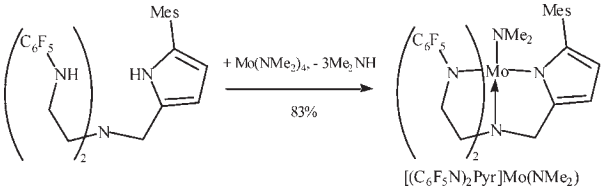
Results

Synthesis of Diamidopyrrolyl Complexes in which Ar = C_6F_5 and Ar′ = Mesityl. A Mannich reaction between 2-mesitylpyrrole[17] and $(C_6F_5NHCH_2CH_2)_2NH$ (eq 1) led to formation of $H_3[(C_6F_5N)_2Pyr]$, a triprotonated version of the trianionic ligand shown in Figure 2 in which Ar = C_6F_5 and Ar′ = Mesityl. $H_3[(C_6F_5N)_2Pyr]$ was obtained as a white powder upon recrystallization of the crude product from a mixture of toluene and pentane.



(1)

An emerald green solution forms rapidly upon mixing solutions of $H_3[(C_6F_5N)_2Pyr]$ and $Mo(NMe_2)_4$ at RT, and green, crystalline, essentially diamagnetic $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ could be isolated in 83% yield (eq 2). A single crystal X-ray diffraction study (Figure 3) showed that the coordination geometry is approximately trigonal bipyramidal with the mesityl substituent on the pyrrolyl ring pointing straight up. The dimethylamido ligand is planar and the N(5)−Mo(1) distance is 1.9383(12) Å, both of which are consistent with the amido ligand being doubly bound to the metal. The plane of the amido ligand is approximately parallel to the plane of the mesityl ring. The Mo(1)−N(4) bond length (2.2630(12) Å) is similar to what is found in related triamidoamine ligand systems, and longer than Mo(1)−N(3) (1.9539(12) Å) and Mo(1)−N(2) (1.9688(12) Å. The Mo(1)−N(1) bond length (2.081 Å) is slightly longer than the $Mo-N_{amido}$ bonds and the average $Mo(1)-N_{pyrrolyl}$ bond length (2.007 Å) in a tris(pyrrolyl-α-methyl)amine molybdenum chloride complex,[15] but approximately what is found for $Mo-N_{pyrrolyl}$ bonds in several molybdenum-η^1-pyrrolyl complexes.[18]



(2)

The chemical shift of the dimethylamido protons in the proton NMR spectrum of $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ is temperature dependent, a phenomenon that is analogous to what is found for the triamidoamine complexes, $[TMSN_3N]Mo(NMe_2)$ ($[TMSN_3N]^{3-} = [(Me_3SiNCH_2CH_2)_3N]^{3-}$)[19] and $[C_6F_5N_3N]Mo(NMe_2)$,[20] and which is consistent with a rapid interconversion of diamagnetic ($S = 0$) and paramagnetic ($S = 1$) forms.[21] The changes in the chemical shifts of the dimethylamido protons in $[TMSN_3N]Mo(NMe_2)$ (~9 ppm from 180 to 304 K) and $[C_6F_5N_3N]Mo(NMe_2)$ (~2.8 ppm from 259−367 K) are larger than in $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ (0.12 ppm from 233−302 K; see Figure S1 in the Supporting Information). If we *assume* that the temperature dependent chemical shifts are a consequence of interconversion of high spin and low spin forms, then $\Delta H°$ is calculated to be 27(15) kJ mol^{-1}; although $\Delta H°$ for $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ cannot be calculated accurately, the energy difference between the high and low spin states of $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ clearly is much greater than that in $[TMSN_3N]Mo(NMe_2)$ ($\Delta H° = 9.9(1.3)$ kJ mol^{-1}) or $[C_6F_5N_3N]Mo(NMe_2)$ ($\Delta H° = 10.2(1.4)$ kJ mol^{-1}).

Addition of $LiN(TMS)_2$ to a mixture of $H_3[(C_6F_5N)_2Pyr]$ and $MoCl_4(THF)_2$ in tetrahydrofuran (THF) results in a rapid color change from red-orange to magenta. Paramagnetic reddish-pink $[(C_6F_5N)_2Pyr]MoCl$ can be isolated from the mixture in 42% yield (eq 3). The solid-state structure of $[(C_6F_5N)_2Pyr]MoCl$ (Figure 4) reveals it to be a TBP species similar to $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ (Figure 3). The Mo(1)−N(1) bond length (2.0184(12) Å) is longer than that for Mo(1)−N(3) (1.9539(12) Å) or

(17) Rieth, R. D.; Mankad, N. P.; Calimano, E.; Sadighi, J. P. *Org. Lett.* **2004**, *6*, 3981.

(18) (a) Marinescu, S. C.; Singh, R.; Hock, A. S.; Wampler, K. M.; Schrock, R. R.; Müller, P. *Organometallics* **2008**, *27*, 6570. (b) Wampler, K. M.; Schrock, R. R. *Inorg. Chem.* **2008**, *47*, 10226. (c) Al Obaidi, N.; Brown, K. P.; Edwards, A. J.; Hollins, S. A.; Jones, C. J.; McCleverty, J. A.; Neaves, B. D. *Chem. Commun.* **1984**, 690. (d) Al Obaidi, N.; Chaudhury, M.; Clague, D.; Jones, C. J.; Pearson, J. C.; McCleverty, J. A.; Salam, S. S. *Dalton Trans.* **1987**, 1733.

(19) Mösch-Zanetti, N. C.; Schrock, R. R.; Davis, W. M.; Wanninger, K.; Seidel, S. W.; O'Donoghue, M. B. *J. Am. Chem. Soc.* **1997**, *119*, 11037.

(20) Kol, M.; Schrock, R. R.; Kempe, R.; Davis, W. M. *J. Am. Chem. Soc.* **1994**, *116*, 4382.

(21) (a) Gütlich, P.; McGarvey, B. R.; Klaeui, W. *Inorg. Chem.* **1980**, *19*, 3704. (b) Klaeui, W.; Eberspach, W.; Gütlich, P. *Inorg. Chem.* **1987**, *26*, 3977. (c) Smith, M. E.; Andersen, R. A. *J. Am. Chem. Soc.* **1996**, *118*, 1119. (d) LaMar, G. N., Horrocks, W. D., Jr.; Holm, R. H., Eds.; *NMR of Paramagnetic Molecules*; Academic: New York, 1973. (e) Kriley, C. E.; Fanwick, P. E.; Rothwell, I. P. *J. Am. Chem. Soc.* **1994**, *116*, 5225. (f) Saillant, R.; Wentworth, R. A. D. *Inorg. Chem.* **1969**, *8*, 1226. (g) Cotton, F. A.; Eglin, J. L.; Hong, B.; James, C. A. *J. Am. Chem. Soc.* **1992**, *114*, 4915. (h) Cotton, F. A.; Chen, H. C.; Daniels, L. M.; Feng, X. *J. Am. Chem. Soc.* **1992**, *114*, 89980. (i) Fettinger, J. C.; Keogh, D. W.; Kraatz, H.-B.; Poli, R. *Organometallics* **1996**, *15*, 5489. (j) Campbell, G. C.; Reibenspies, J. H.; Haw, J. F. *Inorg. Chem.* **1991**, *30*, 171. (k) Boersma, A. D.; Phillipi, M. A.; Goff, H. M. *J. Magn. Reson.* **1984**, *57*, 197.

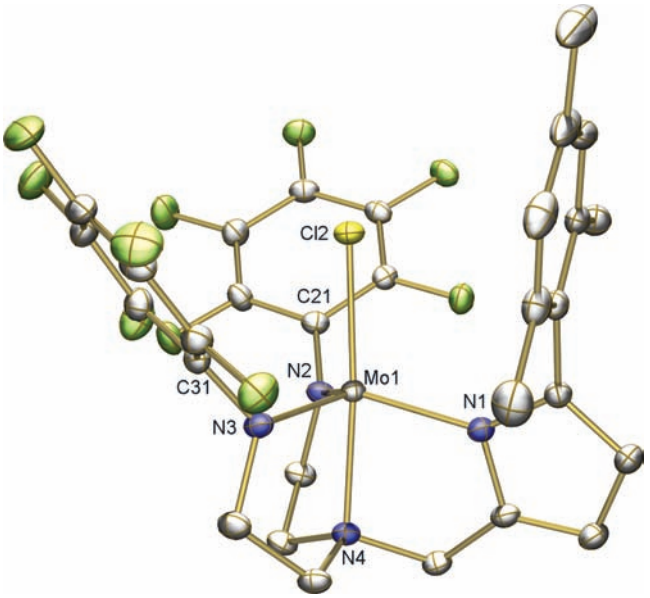
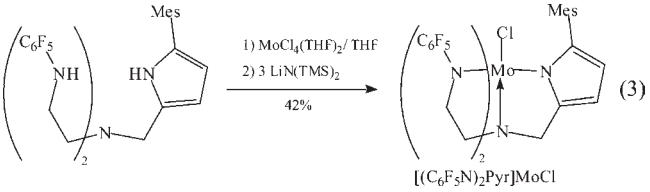


Figure 4. Thermal ellipsoid drawing (50% probability) of the solid state structure of $[(C_6F_5N)_2Pyr]MoCl$. H atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): Cl(2)−Mo(1) = 2.3583(4), Mo(1)−N(3) = 1.9539(12), Mo(1)−N(2) = 1.9688(12), Mo(1)−N(1) = 2.0184(12), Mo(1)−N(4) = 2.1737(12), C(21)−N(2)−Mo(1) = 125.99(10), C(31)−N(3)−Mo(1) = 123.41(10), N(1)−Mo(1)−N(4) = 79.05(5), N(2)−Mo(1)−N(4) = 79.49(5), N(3)−Mo(1)−N(4) = 79.98(5), N(4)−Mo(1)−Cl(2) = 174.98(3).

Mo(1)−N(2) (1.9688(12) Å), as found in $[(C_6F_5N)_2Pyr]$-$Mo(NMe_2)$.

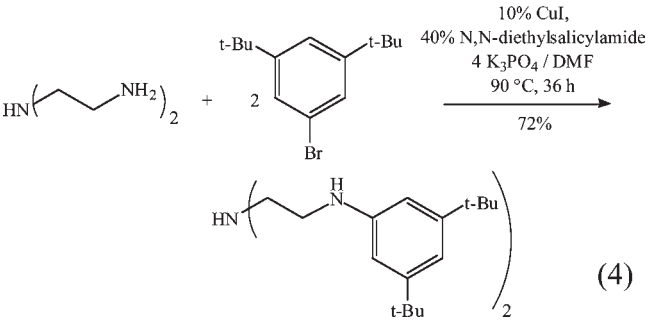


(3)

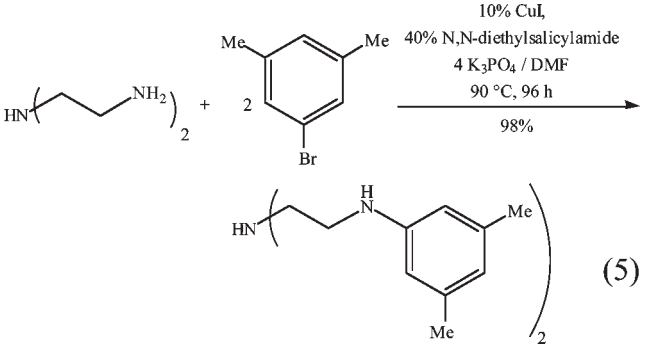
A reaction between $[(C_6F_5N)_2Pyr]MoCl$ and AgOTf led to formation of paramagnetic, orange $[(C_6F_5N)_2Pyr]Mo$-OTf in approximately 40% yield, while a reaction between $[(C_6F_5N)_2Pyr]MoCl$ and NaN_3 in acetonitrile at 70 °C over a period of 72 h led to formation of yellow, diamagnetic $[(C_6F_5N)_2Pyr]MoN$. Both reactions are similar to those reported in related triamidoamine complexes.

Attempts to reduce $[(C_6F_5N)_2Pyr]MoCl$ in THF under dinitrogen with sodium, KC_8, or Mg, or $[(C_6F_5N)_2Pyr]Mo$-(OTf) with Mg powder (activated with 1,2-dichloroethane) so far have not led to any isolable dinitrogen-containing species such as $[(C_6F_5N)_2Pyr]Mo(N_2)$ or $\{[(C_6F_5N)_2Pyr]$-$Mo(N_2)\}^-$. It should be pointed out that the $[(C_6F_5NCH_2$-$CH_2)_3N]Mo$ system[20] also is compromised relative to analogous $[(ArylNCH_2CH_2)_3N]Mo$ systems in which the aryl is not fluorinated as far as syntheses of dinitrogen complexes are concerned. Therefore we turned to the synthesis of diamidopyrrolyl complexes that contain nonfluorinated aryl substituents on the amido ligands.

Synthesis of Diamidopyrrolyl Complexes in which Ar = 3,5-$R_2C_6H_3$ (R = t-Bu or Me) and Ar′ = Mesityl. Diethylenetriamine could be arylated selectively as shown in eqs 4 and 5.[22,23] (3,5-Di-*t*-butylphenylNHCH$_2$CH$_2$)$_2$NH, a dark yellow oil, must be air-sensitive since minimizing exposure of the reaction to air during workup significantly improves the yields. (3,5-dimethylphenylNHCH$_2$-CH$_2$)$_2$NH does not appear to be as air-sensitive as (3,5-di-*t*-butylphenylNHCH$_2$CH$_2$)$_2$NH.

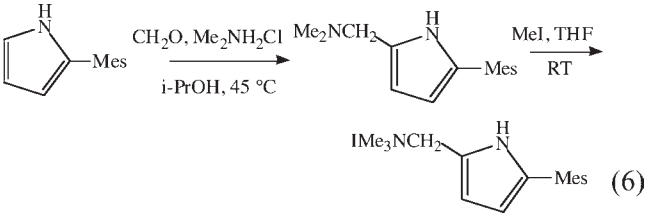


(4)

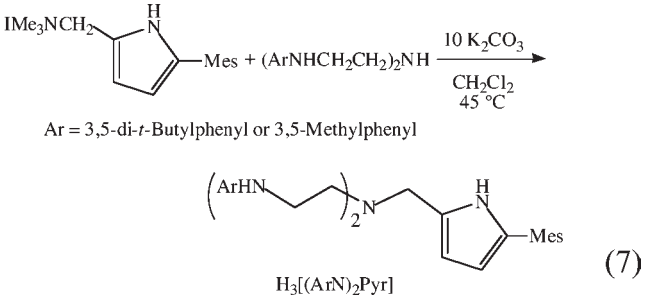


(5)

Mannich reactions analogous to those shown in eq 1 were not successful with the $(ArNHCH_2CH_2)_2NH$ species shown in eqs 4 and 5. However, the approach shown in eqs 6 and 7 was successful. The synthesis of $H_3[(Ar^{t\text{-}Bu}N)_2Pyr]$ had to be carried out in the



(6)



(7)

absence of air. $H_3[(Ar^{t\text{-}Bu}N)_2Pyr]$ could be obtained as a white powder after purification by column chromatography. $H_3[(Ar^{Me}N)_2Pyr]$ does not appear to be as sensitive

(22) Kwong, F. Y.; Klapars, A.; Buchwald, S. L. *Org. Lett.* **2002**, *4*, 581.
(23) Kwong, F. Y.; Buchwald, S. L. *Org. Lett.* **2003**, *5*, 793.

to air as $H_3[(Ar^{t\text{-}Bu}N)_2Pyr]$, and no special precautions are necessary. $H_3[(Ar^{Me}N)_2Pyr]$ was obtained as a pale yellow, viscous oil. We focused on the synthesis and chemistry of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo$ complexes since we felt that the greater steric hindrance afforded by the t-butyl groups was the more desirable of the two alternatives. Unfortunately, although we could synthesize a diamidopyrrolyl ligand in which Ar = HIPT and Ar′ = 2,4,6-triisopropylphenyl (Figure 2), which we believed would have the maximum chance of being sufficiently bulky to protect the metal (see Experimental Section), reactions analogous to those described for synthesizing $[(Ar^{t\text{-}Bu}N)_2Pyr]^{3-}$ complexes described below led only to products that could not be isolated through crystallization.

Addition of $H_3[(Ar^{t\text{-}Bu}N)_2Pyr]$ to $Mo(NMe_2)_4$ yielded teal blue, essentially diamagnetic $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NMe_2)$ in 77% yield. Its diamagnetism is consistent with the $S = 0$ ground state that is a consequence of $Mo-N_{amido}$ π bonding. We propose that its structure is analogous to that shown in Figure 3 for the pentafluorophenyl analogue. If we assume that the temperature dependent chemical shifts are a consequence of interconversion of high spin and low spin forms, then $\Delta H°$ is calculated to be 37(10) kJ mol^{-1}, which is of the same magnitude as $\Delta H°$ for $[(C_6F_5N)_2Pyr]Mo(NMe_2)$ (27(15) kJ mol^{-1}). Therefore it appears that $\Delta H°$ is generally smaller in the triamidoamine systems ($[TMSN_3N]Mo(NMe_2)$[19] and $[C_6F_5N_3N]Mo(NMe_2)$[20]) than in diamidopyrrolyl systems ($[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NMe_2)$ and $[(C_6F_5N)_2Pyr]Mo(NMe_2)$).

Addition of $NaN(TMS)_2$ over a period of 30 min to a mixture of $MoCl_4(THF)_2$ and $H_3[(Ar^{t\text{-}Bu}N)_2Pyr]$ in THF led to an orange-brown solution from which $[(Ar^{t\text{-}Bu}N)_2Pyr]MoCl$ could be isolated in moderate yield; a pure sample was isolated as a pink-tan powder after recrystallization of the crude product from a mixture of pentane and toluene. $[(Ar^{t\text{-}Bu}N)_2Pyr]MoCl$ is extremely sensitive to air and moisture and has paramagnetically shifted ligand resonances in its proton NMR spectrum; paramagnetically shifted resonances are features of all $[ArylN_3N]MoCl$ complexes.

The reaction between $[(Ar^{t\text{-}Bu}N)_2Pyr]MoCl$ and NaN_3 in MeCN at RT results in a color change from orange-brown to dark purple followed by precipitation of a bright yellow solid. The reaction is completed upon heating the mixture to 80 °C, and bright yellow diamagnetic $[(Ar^{t\text{-}Bu}N)_2Pyr]MoN$ could be isolated in moderate yields. X-ray quality crystals of $[(Ar^{t\text{-}Bu}N)_2Pyr]MoN$ were grown from fluorobenzene at −35 °C. The solid state structure (Figure 5) showed $[(Ar^{t\text{-}Bu}N)_2Pyr]MoN$ to be a TBP species analogous to the pentafluorophenyl derivatives reported above. The Mo(1)−N(1) bond length again is slightly longer than the Mo(1)−N(2) and Mo(1)−N(3) bond lengths. The Mo(1)−N(4) bond (2.4134(13) Å) is longer that in the pentafluorophenyl derivatives as a consequence of the nitride ligand being in the apical position (Mo(1)−N(5) = 1.6746(13) Å).

Reduction of $[(Ar^{t\text{-}Bu}N)_2Pyr]MoCl$ with 2.3 equiv of Na under an N_2 atmosphere in THF at RT produced a red solution from which a red solid could be isolated after removal of NaCl and unreacted Na. We propose that this extremely sensitive red solid is the diamagnetic diazenido anion, $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)Na(THF)_x$. IR spectra in C_6D_6 reveal two absorption bands in the expected region for a diazenido anion (1761 cm^{-1} and 1751 cm^{-1}), but only a single absorption band is observed in THF (1766 cm^{-1}).

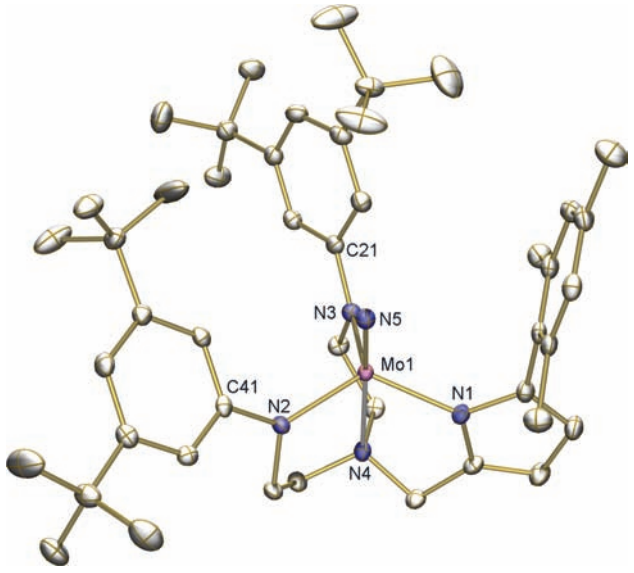


Figure 5. Thermal ellipsoid drawing (50% probability) of the solid state structure of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NMe_2)$. H atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): Mo(1)−N(5) = 1.6746(13), Mo(1)−N(4) = 2.4134(13), Mo(1)−N(1) = 2.0565(12), Mo(1)−N(2) = 1.9857(13), Mo(1)−N(3) = 1.9751(13), C(21)−N(2)−Mo(1) = 126.27(10), C(31)−N(3)−Mo(1) = 127.25(10), N(1)−Mo(1)−N(4) = 75.66(5), N(2)−Mo(1)−N(4) = 76.08(5), N(3)−Mo(1)−N(4) = 80.99(5), N(4)−Mo(1)−N(5) = 176.43(5).

The presence of several diamagnetic species in the ^{1}H NMR spectrum of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)Na(THF)_x$ in C_6D_6 suggests that it is not pure. Attempts to purify the compound through recrystallization were not successful.

When impure $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(THF)_x$ was treated with 1 equiv of 15-crown-5 at −35 °C in diethyl ether, the orange-red solution immediately changed to green and a diamagnetic lilac-colored powder could be isolated from the mixture in ∼20% yield. The lilac-colored compound exhibits a green color and a ν_{NN} absorption at 1855 cm^{-1} in THF, as is found for $\{[HIPTN_3N]Mo(N_2)\}MgCl(THF)_3$ in THF.[8b] All data support formulation of the lilac-colored compound as $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(15\text{-crown-}5)$. When $\{[HIPTN_3N]Mo(N_2)\}Na(THF)_x$[24] is exposed for several hours to a good vacuum, it turns from dark green to purple as a consequence of losing THF; the purple powder dissolves again in THF to yield green solutions. Therefore $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(15\text{-crown-}5)$ either loses 15-crown-5 from the sodium ion in THF or the green color in THF results from complete solvation of the salt in THF.

Reduction of $[(Ar^{t\text{-}Bu}N)_2Pyr]MoCl$ with Na under an atmosphere of dinitrogen followed by addition of Bu_4NCl directly to the reaction mixture yields $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}[NBu_4]$ as a diamagnetic purple solid in ∼60% yield. An IR spectrum of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}[NBu_4]$ reveals a dinitrogen stretch at 1840 cm^{-1} in C_6D_6. Unfortunately, $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}[NBu_4]$ appears to be thermally

(24) $\{[HIPTN_3N]Mo(N_2)\}Na(THF)x$ was synthesized from $[HIPTN_3N]MoCl$ (500 mg, 0.291 mmol) in a manner similar to that employed to synthesize $[HIPTN_3N]Mo(N_2)MgCl(THF)_3$ (ref 8b) using 2 equiv of sodium (mirror) in THF (5 mL). The mixture was stirred with a glass-coated stir bar for 4 days. Solvent was removed in vacuo, the residue was extracted with pentane, and the extract was filtered through Celite. The filtrate was stood overnight at −35 °C, and the emerald green microcrystalline solid obtained was collected on a glass frit; yield 350 mg (69%).

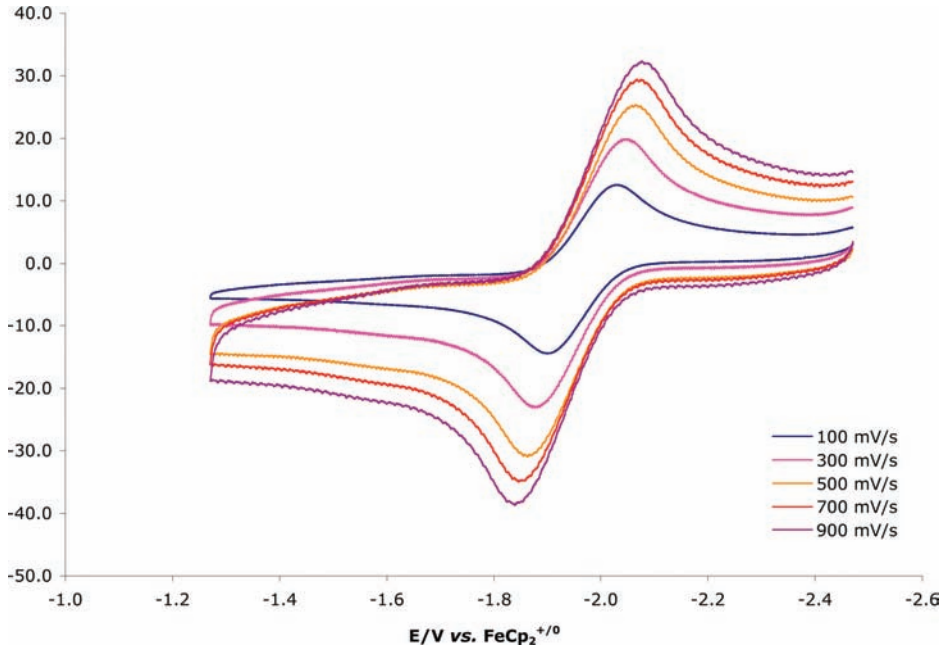


Figure 6. Electrochemical behavior of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}(n\text{-}Bu)_4N$ in 0.1 M $[NBu_4]BAr'_4$ in PhF recorded at a glassy carbon electrode at 100 mV/s to 900 mV/s scan rates, referenced to $Cp_2Fe^{+/0}$. (Vertical axis = current in microamps.)

unstable. It changes color over a period of days in a sealed tube at RT and no samples sent for elemental analyses yielded satisfactory results. We noted in studies of tungsten $[HIPTN_3N]^{3-}$ complexes that $\{[HIPTN_3N]W(N_2)\}[Bu_4N]$ was thermally unstable, although other derivatives (e.g., a potassium salt) could be isolated and characterized. We proposed that the anionic dinitrogen complex is a powerful enough base to react with the tetrabutylammonium cation in the solid state.

$\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}[NBu_4]$ can be oxidized reversibly at −1.96 V in 0.1 M $[NBu_4]BAr'_4$ in PhF as shown in Figure 6. This result should be compared to observation of the reversible $[HIPTN_3N]Mo(N_2)^{0/-}$ redox couple at −2.11 V under similar conditions (0.1 M $[NBu_4]BAr'_4$ in PhF versus $Cp_2Fe^{+/0}$).[8] However, oxidation of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ (anodic peak at ∼ −0.65 V) is not reversible. A reversible $[HIPTN_3N]Mo(N_2)^{0/+}$ couple was observed in PhF, but not in THF as a consequence of rapid displacement of N_2 by THF in the cationic species.[9b] The irreversibility of the $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)^{0/+}$ couple suggests that dinitrogen is lost more readily in $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}^+$ than in $\{[HIPTN_3N]Mo(N_2)\}^+$.

Oxidation of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(THF)_x$ with AgOTf in the dark yielded paramagnetic, red $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ in 53% yield. The value of ν_{NN} in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ (2012 cm^{-1} in C_6D_6) should be compared with ν_{NN} in $[HIPTN_3N]Mo(N_2)$ (1990 cm^{-1} in C_6D_6), a difference of 22 cm^{-1}.[8b] A higher ν_{NN} value in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ is consistent with slightly weaker backbonding into the dinitrogen ligand in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ than in $[HIPTN_3N]Mo(N_2)$.

A mixture of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(THF)_x$ and $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ in C_6D_6 was freeze−pump−thaw degassed and exposed to an atmosphere of $^{15}N_2$. After 2.5 h an IR spectrum of the solution revealed that approximately half the $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ had been converted into $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(^{15}N_2)$ (1944 cm^{-1}) and half the $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(THF)_x$ (1751 cm^{-1}) had been converted into $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo^{15}N_2\}Na(THF)^x$ (1692 cm^{-1}; see Figure 7). These results suggest that the exchange of dinitrogen in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ is much faster than it is in $[HIPTN_3N]Mo(N_2)$, where $t_{1/2}$ for exchange is approximately 35 h at 22 °C.[8e] We propose that formation of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(^{15}N_2)\}Na(THF)_x$ from $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(THF)_x$ is a consequence of electron transfer between neutral and anionic species, rather than exchange directly in the anion. This circumstance is analogous to that observed in the parent system where $^{14}N_2/^{15}N_2$ exchange in $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}[NBu_4]$ is extremely slow, and any exchange that is observed can be attributed to oxidation of a small amount of the anion to $[HIPTN_3N]Mo(N_2)$ and fast electron exchange between $[HIPTN_3N]Mo(N_2)$ with $\{[HIPTN_3N]Mo(N_2)\}[NBu_4]$.[8b]

A plot of $\ln(A_{15N}/A_{total})$ for the dinitrogen exchange reaction in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(^{15}N_2)$ under N_2 in C_6D_6 in a nitrogen-filled glovebox at 22 °C showed that the reaction is first order in [Mo] with $k_{obs} = 1.97 \times 10^{-4}\ s^{-1}$ ($t_{1/2} \sim$ 1 h). When the pressure of N_2 was increased to two atmospheres (15 psi overpressure), $t_{1/2}$ for the exchange reaction decreased to ∼30 min. Although the exchange rate depends on N_2 pressure, that dependence alone does not distinguish between an associative reaction to give a six-coordinate bisdinitrogen intermediate, and rapid reversible loss of dinitrogen from $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ followed by capture of the hypothetical "naked" monopyramidal species, $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo$, by dinitrogen. (See Discussion Section.)

When a PhF solution of $[(Ar^{t\text{-}Bu}N)_2Pyr]MoCl$ in the presence of $NaBPh_4$ is exposed to an atmosphere of NH_3 (dried over Na), a rapid color change is observed from orange-red to burgundy and paramagnetic, yellow $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ could be isolated in 32% yield. This compound is relatively insoluble in toluene. Similar experiments employing $NaBAr'_4$ led to formation of what we propose is the analogous $BAr'_4{}^-$ salt, but we were not

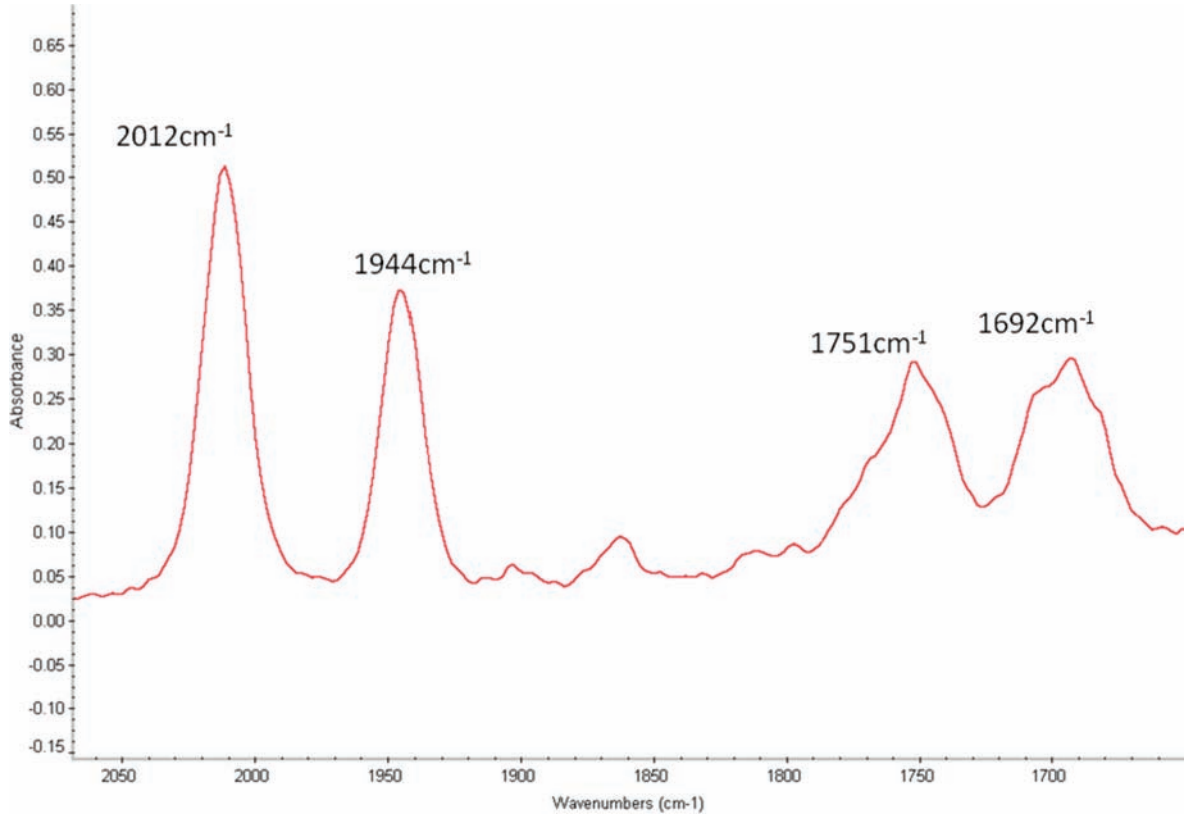


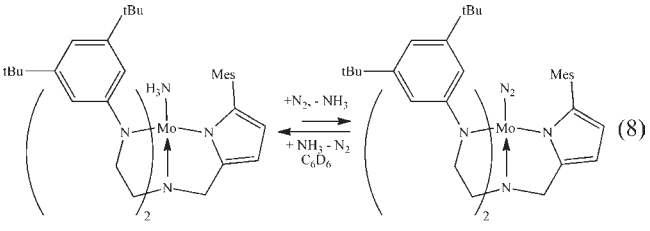
Figure 7. IR spectrum of a C_6D_6 solution of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ and $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}Na(THF)x$ after exposure to $^{15}N_2$ for 2.5 h.

able to isolate this salt from pentane, toluene, CH_2Cl_2, or THF.

Reduction of a THF solution of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH^3)\}BPh_4$ under an Ar atmosphere with $CoCp^*_2$ led to a color change from yellow-brown to green with concomitant formation of yellow $[CoCp^*_2]BPh_4$. THF was removed in vacuo from the emerald green solution and the resulting solid was redissolved in C_6D_6 and exposed to 1 atm of N_2. The color changed from green to red over the course of a day, and IR spectroscopy of the mixture showed that $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ (ν_{NN} = 2012 cm^{-1}) had formed.

The reduction of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ under Ar at approximately −1.68 V at a scan rate of 900 mV/s is not reversible (Figure 8), in contrast to the reduction of $\{[HIPTN_3N]Mo(NH_3)\}^+$, which takes place at −1.63 V and is fully reversible in both PhF and THF. We propose that ammonia is lost from $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)$ upon reduction of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}^+$ even in fluorobenzene. However, when reduction of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ was carried out under dinitrogen at progressively slower scan rates (10 and 50 mV/s), the $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N^2)\}^{0/-}$ redox couple could be observed (Figure 9), thus confirming that dinitrogen replaces ammonia in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)$. The $\{[HIPTN_3N]Mo(N_2)\}^{0/-}$ redox couple is also observed during the electrochemical reduction of $\{[HIPTN_3N]Mo(NH_3)\}^+$.[8c]

Reduction of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ in THF by $CoCp^*_2$ under an Ar atmosphere was followed by removing the THF in vacuo, dissolving the reaction product in C_6D_6, and exposing the solution to 1 atm of dinitrogen. Formation of ~30% of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ is observed after ~5 h. However, if 10 equiv of BPh_3 are present to trap the ammonia that is released, the exchange is virtually complete in about 2 h. Therefore we propose that the equilibrium in eq 8 lies to the left, as it does in the analogous $[HIPTN_3N]^{3-}$ system. Qualitatively, the equilibrium in the $[(Ar^{t\text{-}Bu}N)_2Pyr]^{3-}$ system appears to lie further to the left than in the $[HIPTN_3N]^{3-}$ system, consistent with slightly weaker binding of dinitrogen to the metal in the $[(Ar^{t\text{-}Bu}N)_2Pyr]^{3-}$ system and/or a slightly stronger binding of ammonia, or both.



(8)

Exposure of a solution of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ to an atmosphere of CO led to a color change from red to brown. Brown $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$ could be isolated in 27% yield. $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$ is paramagnetic with a ν_{CO} absorption at 1902 cm^{-1}; an analogous experiment under ^{13}CO yielded $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(^{13}CO)$ ($\nu 13_{CO}$ = 1856 cm^{-1}). It is of utmost importance that the CO employed be free of impurities such as water and oxygen to avoid formation of unknown products with several CO absorption bands in the IR spectrum.

Reaction of a 1:1 mixture of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$ and $[HIPTN_3N]Mo(CO)$ in DME with 1 equiv of $[Collidinium]BAr'_4$ showed that the CO absorption for $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$ (1896 cm^{-1} in DME) disappeared and an absorption for the protonated form is observed at 1920 cm^{-1} (Δ = 24 cm^{-1}). Addition of a second equivalent

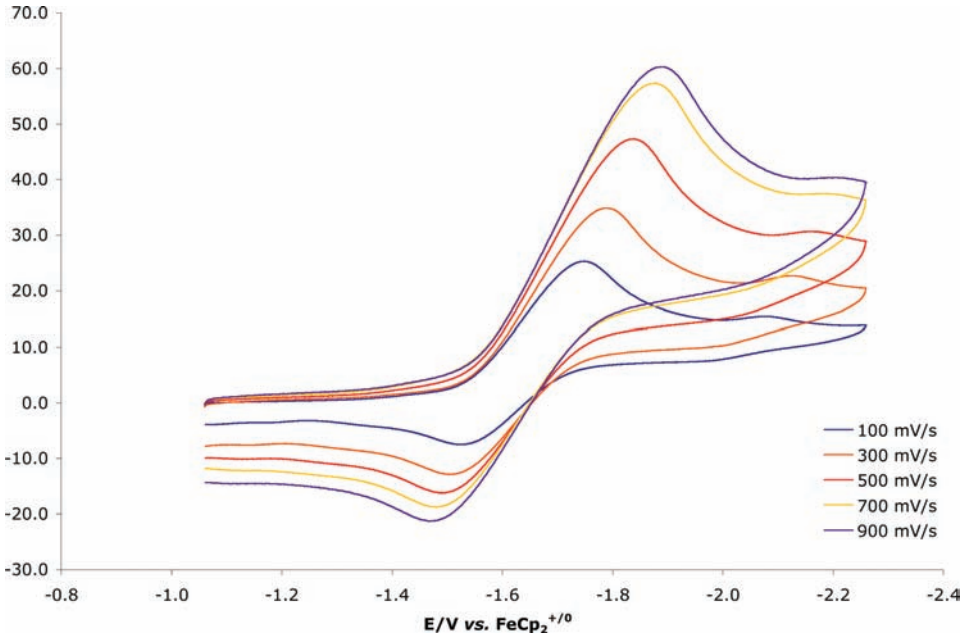


Figure 8. Electrochemical behavior of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ in 0.1 M $[NBu_4]BAr'_4$ in PhF recorded at a glassy carbon electrode, referenced to $Cp_2Fe^{+/0}$. (Vertical axis = current in microamps.)

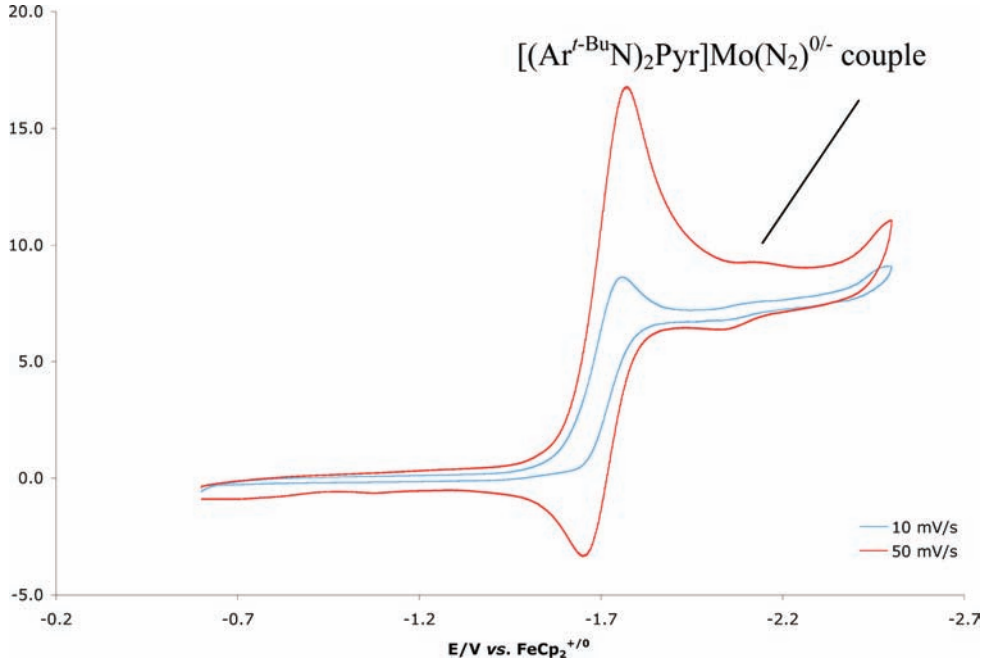


Figure 9. Appearance of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}BPh_4$ at scan rates of 10 and 50 mV/s. (Vertical axis = current in microamps.)

led to protonation of ~50% of the remaining $[HIPTN_3N]$-Mo(CO) (1885 → 1932 cm^{-1}, $\Delta = 47$ cm^{-1}). We conclude that $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$ is protonated more readily than $[HIPTN_3N]Mo(CO)$ and that the shift in ν_{CO} to higher energy in $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)(H)\}^+$ is about half what it is in $\{[HIPTN_3N]Mo(CO)(H)\}^+$. Protonation of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(^{13}CO)$ results in a similar shift in $\nu_{^{13}CO}$ (1853 → 1875 cm^{-1}, $\Delta = 22$ cm^{-1}).

Protonation of $[HIPTN_3N]Mo(N_2)$ is known to lead to loss of intensity of the ν_{NN} stretch at 1990 cm^{-1} and observation of another at 2057 cm^{-1} for $\{[HIPTN_3N]Mo(N_2)$-$(H)\}^+$ ($\Delta = 67$ cm^{-1}). A similar side by side comparison of protonation of a mixture of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ and $[HIPTN_3N]Mo(N_2)$ with $[Collidinium]BAr'_4$ in PhF revealed that $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ was again protonated more readily than $[HIPTN_3N]Mo(N_2)$. Upon addition of 2 equiv of $[Collidinium]BAr'_4$ in PhF all $[(Ar^{t\text{-}Bu}N)_2Pyr]$-$Mo(N_2)$ ($\nu_{NN} = 2012$ cm^{-1}) had disappeared, while most (~70%) of the $[HIPTN_3N]Mo(N_2)$ ($\nu_{NN} = 1990$ cm^{-1}) remained. In a separate experiment involving $[(Ar^{t\text{-}Bu}N)_2$-$Pyr]Mo(N_2)$ in PhF, no ν_{NN} absorption for $\{[(Ar^{t\text{-}Bu}N)_2$-$Pyr]Mo(N_2)(H)\}^+$ could be observed. On the basis of the relative shifts in the CO complexes above (~0.5) we might expect to see ν_{NN} upon protonation of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo$-$(N^2)$ to shift by 0.5×67 cm^{-1} to ~2045 cm^{-1}. Either dinitrogen is lost from $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)(H)\}^+$ more readily

than from $\{[HIPTN_3N]Mo(N_2)(H)\}^+$ or $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)(H)\}^+$ decomposes in some other manner. The site of protonation in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(CO)$ and $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ are assumed to be the same, but whether the site of protonation is the amido nitrogen or the pyrrolide is not known. However, we can say with certainty that $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)(H)\}^+$ is formed more readily than $\{[HIPTN_3N]Mo(N_2)(H)\}^+$, but $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)(H)\}^+$ is less stable, not more stable, than $\{[HIPTN_3N]Mo(N_2)(H)\}^+$.

Attempts to reduce dinitrogen catalytically were carried out with $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N)$ as a "catalyst" in a manner similar to that utilized for $[HIPTN_3N]Mo$ derivatives, including $[HIPTN_3N]MoN$.[8e,f] The amount of NH_3 produced was then quantified using the indophenol method.[25] In three catalytic runs an average of 1.02 ± 0.12 equiv of NH_3 were produced. It is clear that the nitride is reduced to ammonia, but within experimental error we must conclude that the reaction does not turn over under the conditions employed.

Discussion and Conclusions

The results that we have presented suggest that in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo$ compounds the metal is slightly less electron rich than in an analogous $[HIPTN_3N]Mo$ complex. Perhaps the best measure is a value of 2012 cm^{-1} for ν_{NN} in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ in C_6D_6 versus 1990 cm^{-1} in $[HIPTN_3N]Mo(N_2)$ in C_6D_6. Only two $Mo-N_{amido}$ π bonds can form in $[HIPTN_3N]Mo(N_2)$, since the combination of p orbitals on the amido nitrogens that has A_2 symmetry in C_{3v} point group is ligand-centered and nonbonding. Since the pyrrolyl lone pair is part of the six π electron aromatic system in the pyrrolide, the pyrrolyl ligand has little ability to π bond to the metal through the pyrrolyl nitrogen and therefore only two MoN_{amido} π interactions can form in a $[(Ar^{t\text{-}Bu}N)_2Pyr]^{3-}$ complex also. The $[(Ar^{t\text{-}Bu}N)_2Pyr]^{3-}$ and $[HIPTN_3N]^{3-}$ systems turn out to be similar electronically, at least in terms of the degree of activation of dinitrogen.

An important question is whether the reduced π backbonding ability of the metal in a $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo$ complex itself is enough to doom catalytic reduction of dinitrogen. One important step is the exchange of ammonia in the Mo(III) complex with dinitrogen. We have shown (Figure 9) that the $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)\}^{0/-}$ redox couple can be observed upon reduction of $\{[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)\}^+$, thereby verifying that $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)$ is converted readily into $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$. However, evidence suggests that the position of the equilibrium between $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(NH_3)$ and $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ does not lie as far toward the dinitrogen complex as it does in the $[HIPTN_3N]Mo$ system, a finding that is consistent with the slightly poorer backbonding ability of the metal in the $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo$ system. On the whole, it seems that poorer backbonding ability alone is not the primary problem.

More problematic in terms of catalytic reduction, we propose, is the apparent instability of $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo-N{=}NH$. All efforts to prepare or even observe $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo-N{=}NH$ in solution have failed so far. That instability may not be surprising, since in triamidoamine systems where dinitrogen is not reduced catalytically, the $Mo-N{=}NH$ species either is not observable or it is decomposed catalytically in the presence of the conjugate base (e.g., 2,6-lutidine) that builds up after delivery of a proton.[9b,c] In contrast, $[HIPTN_3N]Mo-N{=}NH$ is relatively stable, as is the $Mo-N{=}NH$ species in the analogous (catalytically inactive) hexa-*t*-butylterphenyl system.[9] In general, $Mo-N{=}NH$ species in more "open" ligand systems appear to be compromised in some as yet unknown manner.[9c]

Some measure of the steric hindrance in $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(N_2)$ and similar species is the ease of exchanging dinitrogen. In $[HIPTN_3N]Mo(N_2)$ the exchange of dinitrogen takes place with a first-order rate constant of 6×10^{-6} s^{-1} and a $t_{1/2}$ of approximately 35 h.[8b] In the even more sterically hindered $[HTBTN_3N]Mo$ system (where HTBT is hexa-*t*-butylterphenyl), the exchange of $[HTBTN_3N]Mo(^{15}N_2)$ under $^{14}N_2$ has a $t_{1/2}$ of ~750 h ($k \sim 3 \times 10^{-7}$ s^{-1}).[9] The values for ν_{NN} in the two systems are the same, so the metal$-N_2$ bond strengths are the same. In $[HTBTN_3N]Mo(N_2)$ it is proposed that the steric bulk provided by the t-Bu substituents slows down loss of N_2 from the apical site compared to its rate of loss in $[HIPTN_3N]Mo(N_2)$. The rate constant of the exchange in both $[HIPTN_3N]Mo$ and $[HTBTN_3N]Mo$ systems changes little with the pressure of $^{14}N_2$ (in the range of one to several atmospheres). Although the $Mo-N_2$ bond strength (enthalpy) in $[HIPTN_3N]Mo(N_2)$ is calculated to be 37.8 kcal mol^{-1},[14] inclusion of the entropy term brings down the value for the free energy difference down to as little as half that.[13] Therefore the naked species cannot be discounted as an intermediate on the basis of either experimental data or calculations. The pressure dependence of the dinitrogen exchange $[(Ar^{t\text{-}Bu}N)_2Pyr]Mo(^{14}N_2)$ is proposed to arise through an associative mechanism involving a six-coordinate transition state, a transition state made possible as a consequence of a decrease in steric hindrance around the metal center.

It is unfortunate that complexes that contain a diamidopyrrolyl ligand in which Ar is HIPT and Ar′ is 2,4,6-i-$Pr_3C_6H_2$ (Figure 2) proved too soluble to isolate. It still seems possible that catalytic turnover could be observed in the right steric circumstances. Whether such a diamidopyrrolyl ligand could produce a more efficient catalyst of course is unknown.

Experimental Section

General Procedures. All air and moisture sensitive compounds were handled under N_2 atmosphere using standard Schlenk and glovebox techniques, with flame or oven-dried glassware. Ether, pentane, and toluene were purged with nitrogen and passed through activated alumina columns. Dichloromethane was distilled from a CaH_2 suspension. Pentane was freeze−pump−thaw degassed three times and THF, benzene, tetramethylsilane, benzene-d_6, THF-d_4, and toluene-d_8 were distilled from dark purple Na/benzophenone ketyl solutions. Ether and dichloromethane were stored over molecular sieves in solvent bottles in a nitrogen-filled glovebox while pentane, THF, PhF, benzene, benzene-d_6, THF-d_4 and toluene-d_8 were stored in Teflon-sealed solvent bulbs. Molecular sieves (4 Å) and Celite were activated at 230 °C in vacuo over several days. $(Me_3Si)_2NLi$ (Strem) was sublimed, while $(Me_3Si)_2NNa$ (Aldrich) was recrystallized from THF. $[ZnCl_2(dioxane)]_x$ was prepared by dissolution in diethyl ether and adding 1 equiv of 1,4-dioxane to give. $MoCl_5$ (Strem) was used as obtained, unless indicated otherwise. $MoCl_4(THF)_2$,[26]

(25) (a) Chaney, A. L.; Marbach, E. P. *Clinical Chem.* **1962**, *8*, 130. (b) Weatherburn, M. W. *Anal. Chem.* **1967**, *39*, 971.

(26) Stoffelbach, F.; Saurenz, D.; Poli, R. *Eur. J. Inorg. Chem.* **2001**, *10*, 2699.

$Mo(NMe_2)_4$,[27] 2-mesityl-1*H*-pyrrole[3] were synthesized as referenced. 1-Bromo-3,5-dimethylbenzene and 1-bromo-3,5-di-*tert*-butylbenzene were obtained from Sigma Aldrich; 1-bromo-3,5-di-*tert*-butylbenzene also was synthesized as reported in the literature.[28−30] IR spectra were recorded on a Nicolet Avatar 360 FT-IR spectrometer in 0.2 mm KBr solution cells. NMR spectra were recorded on a Varian Mercury or Varian Inova spectrometer operating at 300 or 500 MHz (1H), respectively. ^1H and ^{13}C NMR spectra are referenced to the residual ^1H or ^{13}C peaks of the solvent. ^{19}F NMR spectra were referenced externally to fluorobenzene (−113.15 ppm upfield of $CFCl_3$). HRMS was performed on a Bruker Daltonics APEXIV 4.7 T Fourier Transform Ion Cyclotron Resonance Mass Spectrometer at the MIT Department of Chemistry Instrumentation Facility. Combustion analyses were performed by Midwest Microlabs, Indianapolis, Indiana, U.S.

H_3[$(C_6F_5N)_2$Pyr]. A 40 mL scintillation vial equipped with a stirbar was charged with N^1-(perfluorophenyl)-N^2-(2-(perfluorophenylamino)ethyl)ethane-1,2-diamine (1.918 g, 4.4 mmol). To formaldehyde (35 wt %, 0.372 mL) was added HCl (5 μL of 12N). THF (1 mL) was added to the formaldehyde mixture, which was then transferred to the 40 mL scintillation vial. To the vial was added THF (2 mL) and isopropanol (2 mL). The mixture was stirred for 20 min, and the reaction mixture added to a vial charged with 2-mesitylpyrrole (0.807 g, 4.4 mmol). The mixture was stirred at RT for 16 h, then washed with 10% KOH solution (40 mL), and extracted with diethyl ether. The extract was dried over Na_2SO_4, the volatiles were removed in vacuo, and the residue was purified by column chromatography using 9: 1 hexanes/ethyl acetate as the eluent. The desired product is the second product from the column, with an Rf value of 0.158; yield 0.1545 g (55%): ^1H NMR (500 MHz $CDCl_3$) δ 7.97 (s, 1H, pyrrole N*H*), 6.92 (s, 2H, Mes 3,5-H), 6.13 (t, 1H, pyrrole −C*H*), 5.96 (t, 1H, pyrrole −C*H*), 4.08 (s, 2H, amine N*H*), 3.72 (s, 2H, C−CH_2-N), 3.35 (q, 4H, $C_6F_5NHCH_2$), 2.78 (q, 4H, $C_6F_5NHCH_2CH_2$), 2.32 (s, 3H, Mes 4-CH_3), 2.09 (s, 6H, Mes 2,6 −CH_3); ^{13}C NMR (126 MHz $CDCl_3$): δ 139.2, 138.2, 137.8, 137.2, 134.7, 132.7, 130.3, 129.8, 128.3, 127.0, 124.0, 108.9, 108.7, 53.9, 51.8, 43.8, 21.2, 20.6 ^{19}F NMR (282 MHz, $CDCl_3$): δ −159.8 (d, J_{FF} = 20.0 Hz, 2,6 -*F*), −164.1 (t, J_{FF} = 21.2 Hz, 3,5 -*F*), −171.3 (tt, J_{FF} = 5.3, 21.9 Hz, 4 -*F*) HRMS (ESI *m*/*z*): Calcd for $C_{30}H_{27}F_{10}N_4^+$ 633.207, found 633.2056.

[$(C_6F_5N)_2$Pyr]Mo(NMe_2). Under a N_2 atmosphere, a 20 mL scintillation vial was charged with $Mo(NMe_2)_4$ (671.8 mg, 2.468 mmol) and $[Mes(C_6F_5)_2]H_3$ (1.338 g, 2.115 mmol) and toluene (15 mL). The reaction mixture rapidly turned dark blue (from deep purple) and eventually became emerald green. It was stirred for approximately 48 h at RT, with the vial periodically uncapped to facilitate loss of $HNMe_2$. The solvent was decreased to approximately 5 mL, and pentane (approximately 2 mL) was added. The reaction mixture was then left at −35 °C overnight and the product collected on a glass frit as a dark green solid; yield 1.347 g (83%): ^1H NMR (toluene-d_8) δ 6.77 (s, 2H, mesityl 3,5-*H*), 6.11 (d, 1H, pyrrole -*H*), 6.02 (d, 1H, pyrrole, -*H*), 3.76 (s, 2H, -NCH_2), 3.72 (quintet, 2H, -C_6F_5NCH(*H*)), 3.23 (quintet, 2H, -C_6F_5NCH(*H*)), 2.97 (quintet, 2H, $C_6F_5NCH_2CH$(*H*)), 2.63 (quintet, 2H, -$C_6F_5NCH_2CH$(*H*)), 2.55 (s, 6H, -N(CH_3)$_2$), 2.17 (s, 3H, mesityl 4-CH_3), 2.04 (s, 6H, mesityl 2,6-CH_3); ^{13}C NMR (toluene-d_8): δ 143.6, 139.7, 137.2, 136.9, 135.2, 129.6, 128.9, 128.8, 128.6 125.8, 113.2, 105.7, 66.2, 61.2, 55.9, 55.1, 21.6, 21.5; ^{19}F NMR (toluene-d_8) δ −148.0 (d), −162.8 (t), −164.7 (t). Anal. Calcd for $C_{32}H_{29}F_{10}MoN_5$: C, 49.95; H, 3.80; N, 9.10. Found: C, 49.67; H, 3.90; N, 9.22.

[$(C_6F_5N)_2$Pyr]MoCl. Under a N_2 atmosphere, a 20 mL scintillation vial equipped with a stir bar was charged with $MoCl_4(THF)_2$ (1.191 g, 3.092 mmol), $[Mes(C_6F_5)_2]H_3$ (2000 mg, 3.162 mmol), and THF (5 mL). The reaction mixture turned from an orange suspension to an orange-red solution. The mixture was stirred for 30 min and $LiNTMS_2$ (1.587 g, 9.484 mmol) was added, which led to a darkening of the mixture to magenta. After stirring the mixture for another 30 min, the volatiles were removed in vacuo, the mixture extracted with toluene, and the extract was filtered through Celite. The product was recrystallized from toluene and pentane at −35 °C and collected on a glass frit; yield 0.989 g (42%): ^1H NMR (C_6D_6) δ 41.03 (s), 12.38 (s), 8.31 (s), 6.84 (s), 6.02 (s), 5.23 (s), 4.34−2.91 (m), 2.12 (s), 1.80 (s), 1.27 (s), 0.88 (s), 0.30 (s), 0.01 (s), −1.21(s), −20.04 (s), −78.50 (s), −92.10 (s); ^{19}F NMR (C_6D_6) δ −71.02 (s), −96.37 (s), −121.893 (s), −122.80 (s), −148.27 (s). HRMS (ESI *m*/*z*): Calcd for $C_{30}H_{23}F_{10}N_4MoClNa^+$: 785.0405, found 785.0412.

[$(C_6F_5N)_2$Pyr]MoOTf. Under a N_2 atmosphere, a scintillation vial was charged with $[Mes(C_6F_5)_2]MoCl$ (100 mg, 0.131 mmol), AgOTf (33.6 mg, 0.131 mmol) and CH_2Cl_2 (5 mL). The mixture was stirred overnight at RT and then filtered through Celite. All volatiles were removed in vacuo. The orange-red product was recrystallized from a mixture of toluene, pentane and CH_2Cl_2; yield 47.5 mg (42%): ^1H NMR (C_6D_6) δ 39.86 (s), 14.85 (s), 12.07 (s), 7.12 (s), 7.06 (s), 7.05 (s), 7.01 (s), 6.35 (s), 4.72 (br s), 2.06 (s), 1.30 −1.24 (m), −21.47 (s), −85.28 (br s), −108.85 (br s). Anal. Calcd for $C_{31}H_{23}F_{13}MoN_4O_3S$: C, 42.58; H, 2.65; N, 6.41. Found: C, 42.40; H, 2.79; N, 6.25.

[$(C_6F_5N)_2$Pyr]MoN. Under a N_2 atmosphere, a 25 mL solvent bulb was charged with $[(C_6F_5N)_2Pyr]MoCl$ (200 mg, 0.263 mmol), NaN_3 (13.6 mg, 0.118 mmol), and acetonitrile (5 mL). The reaction mixture was heated at 70 °C for 72 h. The volatiles were removed in vacuo, and the residue was extracted with toluene and filtered through Celite. Diamagnetic yellow-brown needle-like crystals were deposited after standing the filtrate at −35 °C overnight and collected on a glass frit; yield 103 mg (53%): ^1H NMR (C_6D_6) δ 6.86 (s, 2H, mesityl 3,5-*H*), 6.25 (d, 1H, pyrrole *H*), 6.20 (d, 1H, pyrrole *H*), 3.35 (s, 2H, NCH_2), 3.25 (quintet, 2H, $(NCH(H)CH_2)_3N$), 3.04 (quintet, 2H, $(NCH(H)CH_2)_3N$), 2.48 (s, mesityl 2,6-CH_3), 2.25 (quintet, 2H, $(NCH_2CH(H))_3N$), 2.18 (quintet, 2H, $(NCH_2CH(H))_3N$), 1.92 (s, 3H, mesityl 4-CH_3); ^{13}C NMR (C_6D_6) δ 142.8, 142.5, 140.9, 139.9, 139.0, 139.0 (overlapping), 137.9, 137.8, 137.2, 136.9, 135.1, 133.6, 128.4, 128.1, 111.2, 108.3, 58.3, 51.3, 51.0, 21.1, 21.0, 21.0; ^{19}F NMR (C_6D_6) δ −150.18 (dd, 1F), −150.40 (t, 1F), −159.44 (t, 1F), −163.63 (d, 1F), −163.60 (d, 1F, overlapping). Anal. Calcd for $C_{30}H_{23}F_{10}MoN_5$: C, 48.73; H, 3.14; N, 9.47. Found: C, 48.51; H, 3.28; N, 9.48.

(3,5-*t*-$Bu_2C_6H_3NCH_2CH_2)_2$NH. Under a N_2 atmosphere, a 1 L Schlenk flask was charged with 3,5-di-*tert*-butylbromobenzene (20.78 g, 77.2 mmol), CuI (0.646 g, 3.6 mmol), *N*,*N*-diethylsalicylamide (2.82 g, 14.6 mmol), K_3PO_4 (30.54 g, 143.9 mmol), and a magnetic stirbar. DMF (70 mL) was added and the resulting suspension was stirred for 30−45 min. Diethylene triamine (3.71 g, 36.0 mmol) was added and washed in with DMF (30 mL). The reaction flask was then heated to 90 °C for 36 h with stirring. The initially blue-green mixture turns brown with concomitant formation of reddish Cu powder as the mixture is heated after approximately 2 h. The mixture was allowed to cool to RT, then aqueous NH_3 (100 mL) and H_2O (300 mL) were added with stirring. The mixture was extracted with CH_2Cl_2 (4× 200 mL), and the organic layers were dried over Na_2SO_4. The product was purified via column chromatography first eluting with 4:1 Hexanes/Ethyl acetate and then subsequently with diethyl ether. Care was taken to limit exposure of the product to O_2. The product was obtained as a yellow

(27) Bradley, D. C.; Chisholm, M. H. *J. Chem. Soc. A* **1971**, 2741.
(28) Ditto, S. R.; Card, R. J.; Davis, P. D.; Neckers, D. C. *J. Org. Chem.* **1979**, *44*, 894.
(29) Frampton, M. J.; Akdas, H.; Cowley, A. R.; Rogers, J. E.; Slagle, J. E.; Fleitz, P. A.; Drobizhev, M.; Rebane, A.; Anderson, H. L. *Org. Lett.* **2005**, *7*, 5365.
(30) Nomura, N.; Ishii, R.; Yamamoto, Y.; Kondo, T. *Chem.—Eur. J.* **2007**, *13*, 4433.

oil; yield 12.44 g (72%): ^{1}H NMR (C_6D_6) 7.022 (2H, s, Aryl 4-*H*), 6.589 (4H, s, Aryl 2,6-*H*), 3.776 (2H, ArN*H*), 2.986 (4H, t, ArNHCH_2), 2.509 (4H, t, ArNHCH$_2$CH_2), 1.374 (36H, s, −C-(CH_3)$_3$) HRMS (ESI, *m*/*z*): Calcd for $C_{32}H_{54}N_3^+$: 480.4312, found 480.4294.

(3,5-Me$_2$C$_6$H$_3$NCH$_2$CH$_2$)$_2$NH. A 300 mL Schlenk flask was charged with CuI (0.4507 g, 2.4 mmol), *N*,*N*-diethylsalicylamide (1.826 g, 9.5 mmol), K_3PO_4 (20.07 g, 94.5 mmol), and DMF (50 mL). The mixture was stirred for 30 min. 1-Bromo-3,5-dimethylbenzene (10.0 g, 54.4 mmol) was added, and the mixture was stirred for 5 min before subsequent addition of diethylene triamine (2.44 g, 23.6 mmol) was added and washed in with DMF (30 mL). The reaction flask was then heated to 90 °C for 96 h with stirring. The initially blue-green mixture turns brown with concomitant formation of reddish Cu powder as the mixture is heated after approximately 2 h. The mixture was allowed to cool to RT, then aqueous NH_3 (100 mL) and water (200 mL) were added with stirring. The mixture was extracted with ethyl acetate (4× 200 mL) and the organic layers were dried over Na_2SO_4. The product was purified via column chromatography first eluting with Et_2O to remove impurities and then THF. The product was obtained as a brown-yellow oil; yield 7.200 g (98%): ^{1}H NMR (C_6D_6) δ 6.442 (2H, s, xylyl 4-*H*), 6.268 (4H, s, xylyl 2,6-*H*), 3.791 (2H, br s, ArN*H*CH2), 2.903 (4H, t, ArNHCH_2), 2.448 (4H, t, ArNHCH$_2$CH_2). HRMS (ESI, *m*/*z*): Calcd for $C_{20}H_{30}N_3^+$: 312.2434, found 312.2442.

H$_3$[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]. Under N_2 atmosphere, a 500 mL Schlenk flask was charged with (3,5,-Me$_2$C$_6$H$_3$NHCH$_2$CH$_2$)$_2$NH (12.44 g, 25.9 mmol), 1-(5-mesityl-1*H*-pyrrol-2-yl)-*N*,*N*-trimethylammonium iodide (2) (9.848 g, 25.6 mmol), K_2CO_3 (35.88 g, 259.6 mmol) and THF (250 mL). The reaction was heated to 50 °C for 72 h, with the flask periodically vented to an atmosphere of N_2. The mixture was cooled to RT, then filtered and extracted with Et_2O. The volatiles were removed in vacuo, and the resulting mixture was purified via column chromatography using 4:1 hexanes/ethyl acetate as the eluent; yield 10.44 g (60%): ^{1}H NMR (C_6D_6) δ 7.325 (1H, s, pyrrole N-*H*), 7.009 (2H, t, J_{HH} = 1.7 Hz, Aryl 4-*H*), 6.834 (2H, s, mesityl 3,5-*H*), 6.596 (4H, d, J_{HH} = 1.7 Hz, Aryl 2,6-*H*), 6.214 (1H, dd (apparent triplet), pyrrole C*H*), 6.087 (1H, dd (apparent triplet), pyrrole C*H*), 3.867 (2H, s, ArylN*H*), 3.413 (2H, s, pyrroleCH_2N), 3.041 (4H, t, J_{HH} = 5.8 Hz, ArylNHCH_2), 2.498 (4H, t, J_{HH} = 5.8 Hz, ArylNHCH$_2$CH_2), 2.187, 2.181 (overlapping, 12H, s, mesityl 2,4,6-CH_3), 1.285 (36H, s, Aryl 3,5-C(CH_3)$_3$). ^{13}C NMR (C_6D_6): δ 152.18, 148.05, 138.70, 137.67, 131.784, 130.223, 128.827, 128.68, 128.29, 112.57, 109.39, 108.94, 108.45, 53.46, 52.33, 42.62, 35.35, 32.15, 21.52, 21.32. HRMS (ESI, *m*/*z*): Calcd for $C_{46}H_{67}N_4^+$: 677.5517, found 677.5504

H$_3$[(Ar^{Me}N)$_2$Pyr]. A 500 mL flask was charged with (3,5,-Me$_2$C$_6$H$_3$NHCH$_2$CH$_2$)$_2$NH (7.20 g, 23.1 mmol), 2 (8.80 g, 22.9 mmol), Cs_2CO_3 (16.78 g, 2.3 mmol), and THF. The flask was stoppered with a cap equipped with a needle to prevent pressure build-up. The reaction mixture was stirred for 48 h at 70 °C. The volatiles were removed in vacuo, and the mixture extracted with Et_2O and filtered. The volatiles were removed in vacuo, and the resulting oil purified via column chromatography (3:1 hexanes/ethyl acetate as eluent) to produce a viscous yellow oil; yield 4.181 g (36%): ^{1}H NMR (C_6D_6) δ 7.540 (1H, s, pyrrole N*H*), 6.823 (2H, s, Aryl 4-*H*), 6.393 (2H, s, mesityl 3,5-*H*), 6.227 (4H, s, Aryl 2,6-*H*), 6.201 (1H, t, J_{HH} = 2.6 Hz, pyrrole-*H*), 6.081 (1H, t, J_{HH} = 2.6 Hz, pyrrole-*H*), 3.691 (2H, s, ArylN*H*), 3.342 (2H, s, pyrroleCH_2N), 2.864 (4H, t, J_{HH} = 5.4 Hz, ArylNHCH_2), 2.356 (4H, t, J_{HH} = 5.4 Hz, ArylNHCH$_2$CH_2), 2.203 (12H, s, Aryl 3,5-CH_3), 2.198 (3H, s, mesityl 4-CH_3), 2.158 (6H, s, mesityl 2,6-CH_3); ^{13}C NMR (C_6D_6) δ 149.10, 138.83, 138.41, 137.22, 131.46, 129.94 (quaternary carbons, 1 carbon overlapping with C_6D_6); 128.48, 119.94, 111.43, 108.75, 108.53 (tertiary carbons), 52.96, 51.75, 41.88 (secondary carbons), 21.74, 21.20, 20.94 (primary carbons). HRMS (ESI, *m*/*z*): Calcd for $C_{34}H_{45}N_4^+$ 509.3639; found 509.3640.

***N*,*N*-dimethyl-1-(5-(2,4,6-triisopropylphenyl)-1*H*-pyrrol-2-yl)-methanamine.** A 100 mL round-bottom flask was charged with Me_2NH_2Cl (1.592 g, 19.52 mmol), formaldehyde (1.670 mL, 37% solution in water, 20.58 mmol), and isopropanol (10 mL). The mixture was stirred for approximately 30 min. 2-(2,4,6-Triisopropylphenyl)-1*H*-pyrrole (5.260 g, 19.52 mmol) was then added, and the mixture was stirred for approximately 70 h at 40 °C. A 300 mL portion of 10% KOH solution was added, and the mixture stirred for 30 min. Volatiles were removed in vacuo, and 200 mL of water was added. The mixture was extracted three times with CH_2Cl_2 (200 mL), and the organic layer was dried over Na_2SO_4. Volatiles were removed in vacuo, and the residue was used without further purification: yield 4.35 g (68%): ^{1}H NMR ($CDCl_3$) δ 8.206 (1H, s, pyrrole -N*H*), 7.037 (2H, s, aryl 3,5-*H*), 6.069 (1H, t, J_{HH} = 3.0 Hz, pyrrole C-*H*), 5.953 (1H, t, J_{HH} = 3.0 Hz, pyrrole C-*H*), 3.465 (2H, s, −CH_2), 2.927 (1H, septet, J_{HH} = 6.7 Hz, 4-C*H*Me$_2$), 2.789 (2H, septet, J_{HH} = 6.7 Hz, 2,6-C*H*Me$_2$), 2.223 (6H, s, -N(CH_3)$_2$) ppm; ^{13}C NMR ($CDCl_3$) δ 149.6, 149.1, 129.4, 128.7, 128.3, 120.6, 108.7, 108.3, 56.8, 45.0, 34.6, 30.7, 24.7, 24.3. ppm HRMS (ESI, *m*/*z*): Calcd for $C_{22}H_{33}N_2^-$ 325.2659. Found 325.2650.

1-(5-(2,4,6-Triisopropylphenyl)-1*H*-pyrrol-2-yl)-*N*,*N*-trimethylammonium iodide. A 250 mL round-bottom flask was charged with 1-(5-(2,4,6-triisopropylphenyl)-1*H*-pyrrol-2-yl)-*N*,*N*-dimethylmethanamine (3.950 g, 12.098 mmol) and THF (150 mL). A vial with a septum sealed cap was charged with MeI (1.717 g, 12.098 mmol) and THF (15 mL). The contents of the vial were syringed out and added slowly to the stirring solution of 1-(5-(2,4,6-triisopropylphenyl)-1*H*-pyrrol-2-yl)-*N*,*N*-dimethylmethanamine. The reaction mixture was stirred for 1 h at RT, during which a very thick white suspension formed. The white precipitate was collected on a glass frit, washed with THF, and recrystallized from acetone; yield 3.12 g (55%): ^{1}H NMR ($CDCl_3$) δ 10.05 (1H, s, pyrrole -N*H*), 7.02 (2H, s, mesityl 3,5-*H*), 6.42 (1H, t, J_{HH} = 2.9 Hz, pyrrole C-*H*), 6.01 (1H, t, J_{HH} = 2.9 Hz, pyrrole C-*H*), 5.20 (2H, s, −CH_2), 3.30 (9H, s, N(CH_3)$_3$), 2.92 (1H, septet, J_{HH} = 6.6 Hz, 4-C*H*Me$_2$), 2.60 (2H, septet, J_{HH} = 6.6 Hz, 2,6-C*H*Me$_2$), 1.30 (6H, d, J_{HH} = 7.1 Hz, 4-CH(CH_3)$_2$), 1.15 (6H, d, J_{HH} = 7.1 Hz, 2,6-CH(CH_3)$_2$), 1.12 (6H, d, J_{HH} = 7.1 Hz, 2,6-CH(CH_3)$_2$) ppm; ^{13}C NMR ($CDCl_3$) δ 149.6, 149.2, 133.6, 127.5, 120.8, 116.9, 114.8, 110.4, 62.4, 52.4, 34.5, 30.9, 25.1, 24.3, 24.2 ppm HRMS (ESI, *m*/*z*): Calcd for $C_{23}H_{37}N_2^-$ 341.2951. Found 341.2937.

H$_3$(HIPTN)$_2$(TRIPpyr). A 100 mL round-bottom flask was charged with N^1-HIPT-N^2-(2-(HIPT)ethyl)ethane-1,2-diamine (1.194 g, 1.121 mmol), 1-(5-(2,4,6-triisopropylphenyl)-1*H*-pyrrol-2-yl)-*N*,*N*-trimethylammonium iodide (0.525 g, 1.121 mmol), and K_2CO_3 (1.2 g, 8.682 mmol). The flask was purged with N_2, and the reaction mixture stirred overnight at RT under N_2. The product was purified by column chromatography and eluted with 2:1 hexanes/ethyl acetate; yield 0.7893 g (52%): ^{1}H NMR ($CDCl_3$) δ 7.87 (1H, s, pyrrole −N*H*), 7.01 (2H, s, TRIP aryl 3,5-*H*), 7.01 (8H, HIPT aryl 3,5,3″,5″-*H*), 6.39 (4H, d, HIPT aryl 2′,6′-*H*), 6.37 (2H, t, HIPT aryl 4′-*H*), 6.08 (1H, t, J_{HH} = 2.9 Hz, pyrrole C-*H*), 5.96 (1H, t, J_{HH} = 2.9 Hz, pyrrole C-*H*), 3.92 (2H, t, J_{HH} = 5.1 Hz, N*H*CH$_2$CH$_2$), 3.75 (2H, s, NCH_2C), 3.20 (4H, q, J_{HH} = 5.8 Hz, NHCH_2CH$_2$N), 2.92 (4H, sept, J_{HH} = 7.0 Hz, HIPT 4,4″-C*H*Me$_2$), 2.91 (1H, sept, J_{HH} = 7.0 Hz, TRIP 4-C*H*Me$_2$), 2.81 (12H, sept, J_{HH} = 6.9 Hz, HIPT 2,6,2″,6″ −C*H*Me$_2$ overlapping with NHCH$_2$CH_2N), 2.73 (2H, sept, J_{HH} = 6.9 Hz, TRIP 2,6-C*H*Me$_2$), 1.29 (28H, d, J_{HH} = 6.7 Hz, HIPT 4,4″-CH(CH_3)$_2$, TRIP 4-CH(CH_3)$_2$), 1.12 (24H, d, J_{HH} = 6.7 Hz, HIPT 2,6,2″,6″-CH(CH_3)$_2$), 1.08 (12H, d, J_{HH} = 6.7 Hz, TRIP 2,6-CH(CH_3)$_2$), 1.04 (24H, d, J_{HH} = 6.7 Hz, HIPT 2,6,2″,6″-CH(CH_3)$_2$) ppm; ^{13}C NMR (126 MHz $CDCl_3$) δ 149.5, 147.6, 147.3, 146.5, 141.6, 137.5, 129.0, 128.8, 126.9, 121.5, 120.7, 120.5, 112.5, 109.2, 108.4, 52.7, 51.1, 41.6, 34.6, 30.8, 30.4, 24.7, 24.4, 24.3, 24.2 ppm. HRMS (ESI, *m*/*z*) cald for $C_{96}H_{137}N_4^+$: 1347.0917, found 1347.0863.

[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(NMe$_2$). In a N_2 atmosphere glovebox, a 25 mL solvent bulb equipped with a PTFE screw valve was charged with H_3[(Ar$^{t\text{-Bu}}$N)$_2$Pyr] (635 mg, 0.938 mmol) and $Mo(NMe_2)_4$ (313 mg, 1.15 mmol) and toluene. The reaction mixture turned from purple to ultramarine blue within a couple of hours, but was left to stir at RT overnight. The mixture was brought back into the glovebox and volatiles were removed in vacuo. The desired product was purified via recrystallization from pentane/toluene at −35 °C giving a bright teal blue diamagnetic powder; yield 588 mg (77.0%): ^{1}H NMR (C6D6) δ 7.178 (2H, s, Aryl 4-H), 6.938 (2H, s, mesityl 3,5-*H*), 6.553 (4H, s, Aryl 2,6-*H*), 6.283 (1H, d, J_{HH} = 2.8 Hz, pyrrole C*H*), 6.266 (1H, d, J_{HH} = 2.8 Hz, pyrrole C*H*), 3.963 (2H, dt, ArNCH_2-CH_2), 3.828 (2H, s, pyrroleCH_2N), 3.813 (2H, dt, ArNCH_2-CH_2), 3.200 (2H, dt, ArNCH_2CH_2), 3.006 (6H, s, MoN(CH_3)$_2$), 2.749 (2H, dt, ArNCH_2CH_2), 2.261 (6H, s, mesityl 2,6-CH_3), 2.239 (3H, s, mesityl 4-CH_3), 1.288 (36H, s, Aryl 3,5-C(CH_3)$_3$). Anal. Calcd for $C_{48}H_{71}N_5Mo$: C, 70.82; H, 8.79; N, 8.60. Found: C, 70.47; H, 8.41; N, 8.46.

[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]MoCl. In a N_2 atmosphere glovebox, a 20 mL scintillation vial was charged with H_3[(Ar$^{t\text{-Bu}}$N)$_2$Pyr] (890 mg, 1.3 mmol) and THF (10 mL). The solution was stirred for 5 min to ensure complete dissolution of the ligand. $MoCl_4(THF)_2$ (515.6 mg, 1.4 mmol) was added very slowly with stirring over the course of 30 min. The resulting dark brown solution was stirred for 40 min at RT. $NaN(TMS)_2$ (770.2 mg, 4.2 mmol) was added slowly over 15 min to the mixture, which turned from brown to dark brownish orange. The mixture was stirred for 30 min, and the volatiles were removed in vacuo. The residue was extracted with toluene, and the extract was filtered through Celite. The toluene was removed in vacuo, and the mixture triturated with pentane and cooled to −35 °C overnight. The desired product was collected on a glass frit as a paramagnetic pink-tan powder; yield 0.564 g (53%): ^{1}H NMR (C_6D_6) δ 18.78 (s), 11.71 (br s), 8.20 (s), 5.94 (s), 5.20 (s), 5.10 (s, overlapping), 2.56 (s), 1.82 (36H, s, Aryl 3,5 −C(CH$_3$)$_3$), −24.56 (br s), −83.71 (br s), −115.23 (br s). Anal. Calcd for $C_{46}H_{65}N_4MoCl$: C, 68.60; H, 8.13; N, 6.96. Found: C, 68.62; H, 8.01; N, 6.86.

[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]MoN. In a N_2 atmosphere glovebox, a 25 mL solvent bulb equipped with a PTFE screw valve was charged with [(Ar^{Me}N)$_2$Pyr]MoCl (100 mg, 0.12 mmol), NaN_3 (8.1 mg, 0.12 mmol), and MeCN (10 mL). The reaction mixture was stirred at RT for 10 h, turning from orange brown to purple overnight, with formation of a yellow precipitate. The reaction flask was then brought out of the glovebox and heated at 80 °C for 24 h. The flask was brought back into the glovebox, the volatiles removed in vacuo, and the residue extracted with toluene and filtered through Celite. The volume of the filtrate was decreased to 5 mL and cooled to −35 °C overnight. The resulting yellow precipitate was collected on a glass frit and washed with cold pentane. The product obtained is a bright yellow diamagnetic powder; yield 45 mg (46.2%): ^{1}H NMR (C_6D_6) δ 7.454 (4H, d, J_{HH} = 1.7 Hz, Aryl 2,6-*H*), 7.262 (2H, t, J_{HH} = 1.7 Hz, Aryl 4-*H*), 6.913 (2H, s, mesityl 3,5-*H*), 6.345 (2H, s, pyrrole-*H*), 3.594 (2H, dt, ArylNCH_2CH_2), 3.561 (2H, dt, ArylNCH_2CH_2), 3.531 (2H, s, pyrroleCH_2N), 2.437 (6H, s, mesityl 2,6-CH_3), 2.338 (2H, dt, ArylNCH_2CH_2), 2.278 (3H, s, mesityl 4-CH_3), 2.261 (2H, dt, ArylNCH_2CH_2), 1.318 (36H, s, Aryl 3,5-C(CH_3)$_3$). Anal. Calcd for $C_{46}H_{65}N_5Mo$: C, 70.47; H, 8.36; N, 8.93. Found: C, 70.47; H, 8.44; N, 9.02.

{[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(N$_2$)}Na(15-crown-5). In a N_2 atmosphere glovebox, a 20 mL scintillation vial was charged with {[(3,5-*t*-BuN)$_2$Pyr]Mo(N$_2$)}Na(THF)$_x$ (150 mg, ∼ 0.15 mmol) and Et_2O (5 mL). A separate vial was charged with 15-crown-5 ether (33 mg, 0.15 mmol) and Et_2O (5 mL). Both vials were chilled at −35 °C for 1 h, then the solution of the crown ether was slowly added with stirring to the diazenide solution. An immediate color change is observed, from orange-red to green. The diamagnetic lilac solid was recrystallized from THF at −35 °C; yield 28.5 mg (20%): ^{1}H NMR (THF-d$_8$) δ 7.303 (4H, s, Aryl 2,6-*H*), 6.927 (2H, s, Aryl 4-*H*), 6.627 (2H, s, mesityl 3,5-*H*), 5.983 (1H, d, J_{HH} = 3.0 Hz, pyrrole-C*H*), 5.852 (1H, d, J_{HH} = 3.0 Hz, pyrrole-C*H*), 3.926 (2H, dt, ArylNCH_2CH_2N), 3.861 (2H, dt, ArylNCH_2CH_2N), 3.603 (2H, dt, overlapping with solvent peak, ArylNCH_2CH_2N), 3.482 (2H, s, overlapping with 15-c-5 ^{1}H peak, pyrrolylCH_2N), 3.409 (20H, s, 15-crown-5 -OCH_2CH_2O−), 2.497 (2H, t, J_{HH} = 5.7 Hz, ArylNCH_2CH_2N), 2.174 (3H, s, mesityl 4-CH_3), 2.126 (6H, s, mesityl 2,6-CH_3), 1.230 (36H, s, Aryl 3,5-C(CH_3)$_3$). IR (THF) ν_{NN} 1855 cm^{-1}. Anal. Calcd for $C_{56}H_{85}N_6MoNaO_5$: C, 64.60; H, 8.23; N, 8.07. Found: C, 64.59; H, 8.10; N, 7.98.

{[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(N$_2$)}(*n*-Bu)$_4$N. In a N_2 atmosphere glovebox, a 20 mL scintillation vial was charged with **5a** (700 mg, 0.87 mmol), Na (45.9 mg, 2.00 mmol), and THF (10 mL). The reaction mixture was stirred for 12 h at RT with a glass stirbar, with a concomitant color change from orange red to dark purple to red. The mixture as filtered through Celite and NBu_4Cl (TBACl) (252.9 mg, 1.04 mmol) was added. The mixture turned orange, then dark green after stirring for 40 h at RT. Volatiles were removed in vacuo, then the residue was extracted with toluene and filtered through Celite. The filtrate was decreased in vacuo, with a color change from green to purple. The solution was chilled at −35 °C overnight, and the resulting diamagnetic lavender powder was collected on a glass frit; yield 550 mg (61%): ^{1}H NMR (C_6D_6) δ 7.331 (4H, s, Aryl 2,6-H), 7.057 (2H, s, mesityl 3,5-H), 6.962 (2H, s, Aryl 4-H), 6.771 (1H, d, J_{HH} = 2.9 Hz, pyrrole-H), 6.735 (1H, d, J_{HH} = 2.9 Hz, pyrrole-H), 4.018 (2H, dt, ArylNHCH_2CH_2), 3.849 (2H, dt, ArylNHCH_2-CH_2), 3.481 (2H, s, pyrroleCH_2N), 2.740 (6H, s, mesityl 2,6-CH_3), 2.399 (3H, s, mesityl 4-CH_3), 2.382 (2H, dt, ArylNHCH_2-CH_2), 2.252 (2H, dt, ArylNHCH_2CH_2), 2.136 (8H, m, N-(CH_2CH_2CH_2CH$_3$)$_4$), 1.490 (36H, s, Aryl 3,5-C(CH_3)$_3$), 0.996 (8H, m, N(CH_2CH_2CH_2CH$_3$)$_4$), 0.755 (20H, m, N(CH_2CH_2-CH_2CH$_3$)$_4$). IR (C_6D_6) ν_{NN} 1840 cm^{-1}.

[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(N$_2$). In a N_2 atmosphere glovebox, a 20 mL scintillation vial was charged with [(Ar$^{t\text{-Bu}}$N)$_2$Pyr]MoCl (1.431 g, 1.78 mmol), Na (94 mg, 4.09 mmol), and THF (10 mL). The reaction mixture was stirred for 12 h at RT with a glass stirbar, then filtered through Celite. AgOTf (457 mg, 1.78 mmol) was added, and the reaction mixture stirred in the dark for 12 h at RT. Volatiles were removed in vacuo, and the residue was extracted with toluene and filtered through Celite. The filtrate was reduced to 5 mL, and pentane (5 mL) was added. The solution was left at −35 °C overnight, and the resulting paramagnetic reddish-pink precipitate was collected on a glass frit, washed with cold pentane, and dried; yield 746 mg (53%): ^{1}H NMR (C_6D_6) δ 21.855 (2H, br s, ArylNCH_2CH_2N), 21.044 (2H, br s, ArylNCH_2CH_2N), 18.526 (2H, br s), 15.909 (2H, br s, ArylNCH_2CH_2N), 14.900 (2H, br s, ArylNCH_2CH_2N), 8.214 (2H, s), 2.500 (2H, s), 0.601 (36H, br s, Aryl 3,5-C(CH_3)$_3$), −4.423 (6H, br s, mesityl 2,6-CH_3), −7.235 (3H, br s, mesityl 4-CH_3), −23.100 (2H, br s), −42.300 (4H, br s). IR (C_6D_6) ν_{NN} 2012 cm^{-1} (C_6D_6), $\nu^{15}{}_N{}^{15}{}_N$ 1944 cm^{-1} (C_6D_6). Anal. Calcd for $C_{46}H_{65}N_6Mo$: C, 69.24; H, 8.21; N, 10.53. Found: C, 69.03; H, 8.46; N, 10.18.

{[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(NH$_3$)}BPh$_4$. In a N_2 atmosphere glovebox, a 100 mL solvent bulb equipped with a PTFE screw valve was charged with [(Ar$^{t\text{-Bu}}$N)$_2$Pyr]MoCl (622.5 mg, 0.77 mmol), $NaBPh_4$ (290.9 mg, 0.85 mmol) and PhF (15 mL). The bulb was brought out of the glovebox, and freeze−pump−thaw degassed three times. Anhydrous NH_3 (100 mL, 1 atm) which was dried over Na was vacuum transferred into the degassed solvent bulb with the reaction mixture. The mixture immediately changed from orange-red to burgundy. The reaction was stirred for 12 h at RT. The bulb was brought back into the glovebox, and the volatiles were removed in vacuo. The residue was extracted with toluene and filtered through Celite. The filtrate was cooled to −35 °C overnight, then filtered through a glass frit to remove a dark reddish solid. The volume of the resulting yellow-brown

filtrate was decreased to 5 mL, and pentane (15 mL) was added to precipitate a yellow brown solid. The mixture was chilled to −35 °C for 1 h and then filtered through a glass frit to collect the paramagnetic yellow solid; yield 268 mg (32%): ^{1}H NMR (THF-d_8) δ 33.011 (br s), 30.208 (br s), 9.971 (br s), 7.301 (2H, s, Aryl 4-*H*), 7.215 (4H, s, Aryl 2,6-*H*), 6.821 (4H, s) 6.691 (2H, s, pyrrole-*H*), 5.885 (br s), 4.848 (br s), 1.635 (s, Aryl 3,5-C(CH_3)$_3$), −24.605 (br s), −91.744 (br s). Anal. Calcd for $C_{70}H_{88}BMoN_5$: C, 76.00; H, 8.02; N, 6.33. Found: C, 75.60; H, 7.90; N, 6.34.

[(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(CO). In a N_2 atmosphere glovebox, a 100 mL solvent bulb equipped with a PTFE screw valve was charged with [(Ar$^{t\text{-Bu}}$N)$_2$Pyr]Mo(N_2) (250 mg, 0.313 mmol) and benzene. Outside the glovebox, the bulb was freeze−pump−thaw degassed three times, and then CO (1 atm, 100 mL) was vac-transferred into this bulb from another bulb kept at −78 °C (to freeze out water vapor that may be present in the CO gas). The mixture was warmed to RT and stirred over 12 h. The reaction mixture was brought back into the N_2 atmosphere glovebox whereby benzene was removed in vacuo and toluene added to the residue. The toluene solution was chilled at −35 °C overnight, and the resulting paramagnetic green-brown precipitate was collected on a glass frit, washed with pentane, and dried; yield 159 mg (64%): ^{1}H NMR (C_6D_6) δ 20.13 (2H, br s, ArylNCH_2CH_2N), 17.24 (2H, s, ArylNCH_2CH_2N), 13.83 (1H, s, pyrrole-*H*), 12.25 (2H, br s, ArylNCH_2CH_2N), 8.69 (2H, s, Aryl 4-*H*), 7.88 (4H, s, Aryl 2,6-*H*), 3.02 (1H, s, pyrrole-*H*), 1.82 (2H, s), 0.69 (36H, br s, Aryl 3,5-C(CH_3)$_3$), −0.40 (2H, s), −3.72 (6H, s, mesityl 2,6-CH_3), −7.54 (3H, br s, mesityl 4-CH_3), −19.63 (2H, br s), −34.28 (2H, br s). IR (DME) ν_{NN} 1902 cm^{-1}, $\nu^{15}{}_N{}^{15}{}_N$ 1856 cm^{-1}. Anal. Calcd for $C_{47}H_{65}N_4MoO$: C, 70.74; H, 8.21; N, 7.02. Found: C, 70.99; H, 8.11; N, 6.96.

Acknowledgment. Research support from the National Institutes of Health (GM 31978) is gratefully acknowledged.

Supporting Information Available: Crystal data, structure refinement tables for all X-ray structural studies, and tables of selected bond lengths angles. This material is available free of charge via the Internet at http://pubs.acs.org.