Mono- and Bimetallic Rhodium(I) Complexes Supported by New C_2-Symmetric Bis-N-heterocyclic Carbene Ligands: Metalation via C=C Bond Cleavage under Mild Conditions

Matthew S. Jeletic, Ion Ghiviriga, Khalil A. Abboud, and Adam S. Veige*

Center for Catalysis, University of Florida, P.O. Box 117200, Gainesville, Florida 32611

Received June 24, 2007

Summary: The first example of a tethered chiral enetetramine is presented along with its mild metalation with Rh(I) sources to produce chiral, bis-N-heterocyclic carbene complexes. Subtle steric effects determine whether an enetetramine is accessible versus a free biscarbene.

Chiral phosphines are ubiquitous ancillary ligands in metal-catalyzed enantioselective synthesis, yet they still inspire intense research. In particular, C_2-symmetric chelating phosphine ligands are wildly successful in many metal-catalyzed enantioselective reactions, most notably the synthesis of L-DOPA.[1] The first N-heterocyclic carbene complexes were reported 40 years ago,[2] yet, despite Arduengo's landmark 1991 discovery of a free NHC,[3] chiral C_2-symmetric chelating NHC ligands remain scarce.[4,5] Ligand design is still guided by an empirical approach with new and better ligands being built upon previous examples. Some degree of predictability has emerged for phosphorus ligands based on the Tolman map,[6] but no such parameters exist for NHCs. Nonetheless, NHCs do offer potential advantages over phosphines in that they can create stronger M−L bonds, are nonpyrophoric, nontoxic, easily modified, and thus logically represent the next advance in enantioselective catalysis.[7] In principle any reaction catalyzed by a metal−phosphine complex may be similarly catalyzed by an appropriate NHC complex. Considering the breadth of successful phosphine ligands, we began synthesizing mimics based upon the C_2-symmetric (+/−) *trans*-9,10-dihydro-9,10-ethanoanthracene-11,12-bis(1-alkyl)-benzimidazolidine-2-ylidenes, abbreviated (+/−) [DEAM-RBY] (where R = Me, or ^{i}Pr).[8] This platform is chosen to facilitate modification of ligand sterics, electronics, and bite angle in high yield, under mild conditions, on a multigram scale in four or fewer synthetic steps from cheap commercially available starting reagents.[9] Accordingly, herein is reported the synthesis, characterization, and reactivity of new, C_2-symmetric chelating NHC ligands.

Rhodium NHC complexes can be formed directly from imidazolium salts, transmetalation from Ag(I), oxidative addition of C−X bonds (where X = halide, H, and SR), or the equally convenient method of first generating a free carbene followed by metalation.[10] By treating **1-Me**[11] and **1-^{i}Pr** with 2 equiv of $KN(SiMe_3)_2$ in THF, enetetramine **2** and biscarbene **3** are formed in good yield (Scheme 1).[12,8b] Both compounds are characterized by NMR spectroscopy, elemental analysis, and X-ray crystal-

* Corresponding author. E-mail: veige@chem.ufl.edu.

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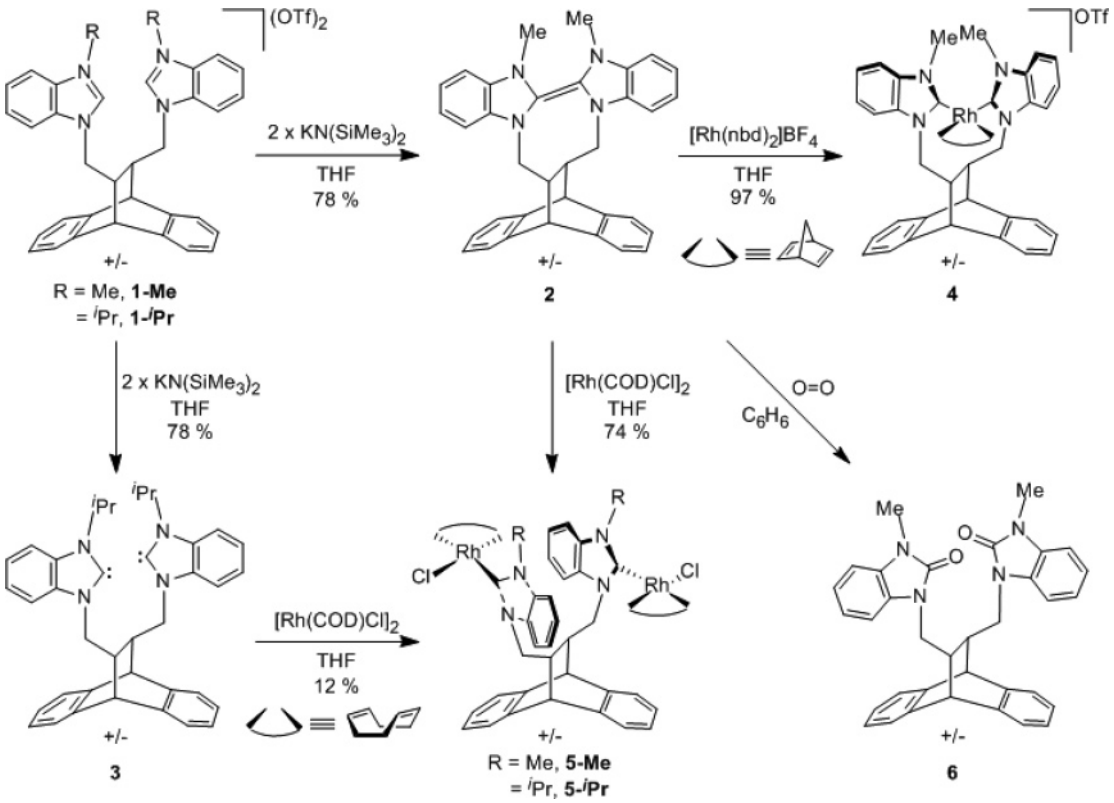
(11) Crystal Data: **1-Me**: $C_{42}H_{48}N_4F_6O_8S_3$, $M = 947.02$, triclinic, space group $P\bar{1}$ $a = 8.9058(6)$ Å, $b = 15.2241(11)$ Å, $c = 17.3077(12)$ Å, $U = 2304.8(3)$ Å^3, $Z = 2$, $D_c = 1.365$ g cm^{-3}, $T = 173(2)$ K, $\mu = 0.239$ mm^{-1}, $wR_2 = 0.1326$ (9009 independent reflections), $R_1 = 0.0525$ [$I > 2\sigma(I)$].

(12) The synthesis of each compound is carried out as a racemic mixture though the same protocols apply for individual enantiomers. Resolution can be accomplished via several methods: (a) Ramanathan, C. R.; Periasamy, M. *Tetrahedron: Asymmetry* **1998**, *9*, 2651. (b) Thunberg, L.; Allenmark, S. *Tetrahedron: Asymmetry* **2003**, *14*, 1317.

10.1021/om700630u CCC: $37.00
Publication on Web 09/27/2007

Scheme 1



lography.[13] Although previous reports suggest the existence of a detectable equilibrium for various enetetramines and their free carbene forms,[14] no such equilibrium is observed for **2** or **3**. Instead, a $^{13}C\{^1H\}$ NMR spectrum of **2** revealed only a single resonance at 126 ppm, which was assigned to the C═C bond of the enetetramine and confirmed by a DEPT experiment.[15] For **3**, only a single carbene resonance is observed downfield at 226 ppm. X-ray diffraction results clearly indicate that no C−C bond is present in the solid state for **3**, but a short C−C bond is observed for **2**[16] (d(C1−C9) = 1.347(3) Å) and compares favorably with other enetetramines.[14,17,18] Considerable strain is present in **2**, evidenced by a 25° dihedral angle along the C−C bond. Clearly the larger ^{i}Pr group is sufficient to cleave or prevent enetetramine formation and provides only the stable free carbene. Compound **2** represents the first example of a tethered chiral enetetramine, and compound **3** adds to the short list of known chiral biscarbene species.[5a,b,f,h,j]

Metalation reactions using enetetramines as NHC ligand precursors typically require elevated temperatures and long reaction times,[18,19] although some mild metalations are reported.[14a,19b] However, by treating **2** with 1 equiv of $[Rh(nbd)_2][BF_4]$ under mild conditions (25 °C, 12 h) the mononuclear, chiral rhodium(I) complex (+/−) [(DEAM-MBY)Rh(nbd)][OTf] (**4**)[20] is produced in excellent yield (97%, Scheme 1). A ^{1}H NMR spectrum of **4** revealed an elaborate set of resonances that each integrated to one proton. Clearly the molecular symmetry of **4** is lower than C_2. In fact, a single-crystal X-ray diffraction experiment revealed the product was C_1-symmetric and not the expected C_2 symmetry of the ligand. Thus, every proton on **4** is chemically and magnetically distinct.[15] The molecular structure of **4** is presented in Figure 1 along with a perspective from above that clearly displays the lowered symmetry.

The smooth C═C bond cleavage to form **4** under mild conditions prompted us to further examine the chemistry of the enetetramine.[19] Dioxygen reacts instantaneously with **2** to cleave the C═C bond and form diurea **6** in quantitative yield. To confirm the identity of the dioxygen splitting product, an authentic sample of **6** was prepared by treating **2** with a stoichiometric amount of PhIO; the reaction is instantaneous and quantitative. Once attached to a metal however, the ligand is rendered inert to oxygen and water. Compound **4** is stable in refluxing wet, oxygenated DMSO-d_6.

By choosing a dinuclear metal reagent, C_2-symmetric complexes can be obtained. Compounds **2** and **3** react with

(13) The molecular structure of **3** was determined by X-ray diffraction. Crystal Data: **3**: $C_{42}H_{46}N_4O_4$, M = 622.83, monoclinic, space group $C2/c$, a = 19.3658(11) Å, b = 15.2156(9) Å, c = 11.4987(6) Å, U = 3334.0(3) Å^3, Z = 4, D_c = 1.241 g cm^{-3}, T = 173(2) K, μ = 0.075 mm^{-1}, wR_2 = 0.1286 (3777 independent reflections), R_1 = 0.0500 [$I > 2\sigma(I)$].

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(15) See Supporting Information.

(16) Two crystal morphologies (orthorhombic, $Pna2_1$, and monoclinic, $P2(1)/c$) of enetetramine **2** precipitate together from concentrated THF solutions at room temperature. Similar metric parameters are observed for both morphologies.

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(20) During routine preparation of **2** the KOTf product is not removed to minimize the number of synthetic manipulations. Upon formation of **3**, the BF_4^- ion is therefore substituted with $^-$OTf.

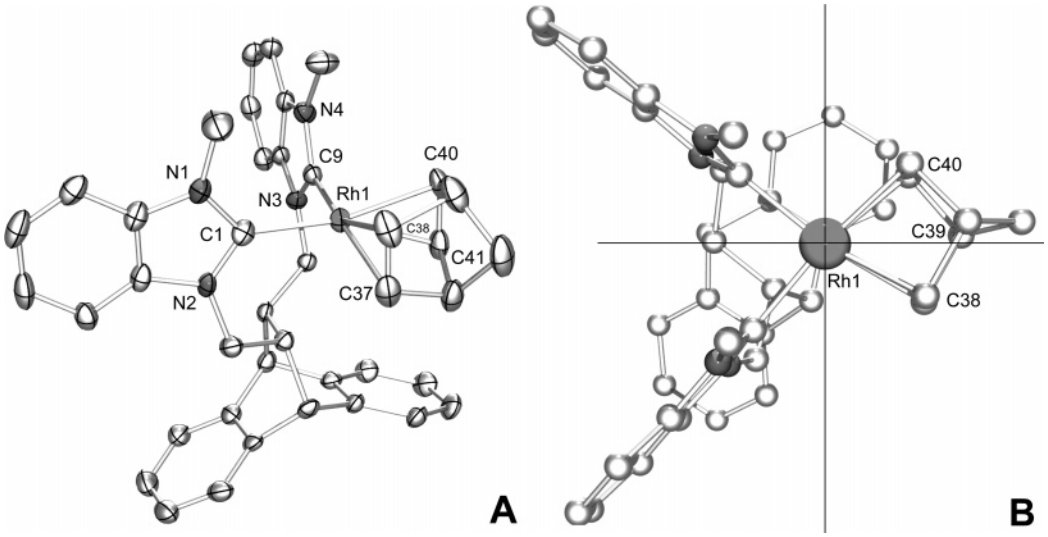

Figure 1. (A) Molecular structure of (+/−) [(DEAM-MBY)Rh(nbd)][OTf] (**4**) with ellipsoids drawn at the 50% probability level. Hydrogen atoms and triflate ion are removed for clarity. (B) Top view of **4**.

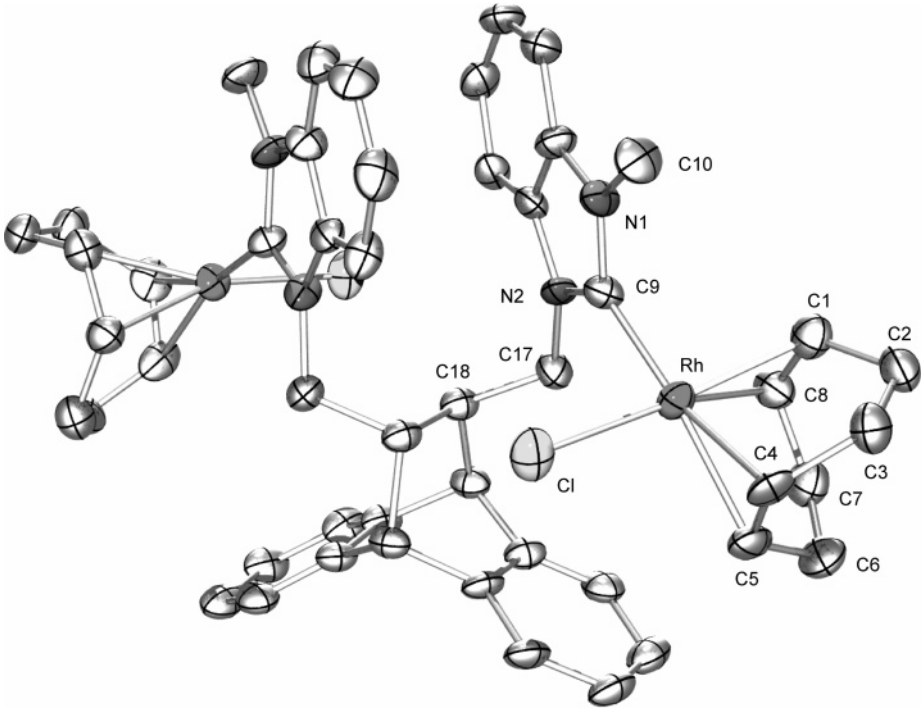

Figure 2. Molecular structure of (+/−) [μ^2-DEAM-MBY][Rh(COD)Cl]$_2$ (**5-Me**) with ellipsoids drawn at the 50% probability level. Hydrogen atoms are removed for clarity.

[Rh(COD)Cl]$_2$ at 25 °C to form dinuclear (+/−) [μ^2-DEAM-RBY][Rh(COD)Cl]$_2$ (**5-R**) (R = Me, ^{i}Pr; Scheme 1). Undisturbed reaction mixtures deposit yellow crystals of **5-R** after 12 h. The result of an X-ray diffraction experiment performed on a single crystal of **5-Me**[21] is presented in Figure 2. The C_2-symmetric complex contains two square-planar Rh(I) centers that orient away from each other. Each Rh(I) center is in a C_1-symmetric environment and is bound to the ligand through a carbene bond (Rh−C9 = 1.998(6) Å). Evidence of π-stacking is observed between the two benzimidazolidine rings, which are coplanar and separated by only 3.54 Å. Unfortunately the low solubility of **5-Me** prohibited spectroscopic analysis, but **5-^{i}Pr** is readily soluble and was characterized by multinuclear and two-dimensional NMR techniques.[15]

This report establishes the synthesis of two new C_2-symmetric chelating bis-*N*-heterocyclic carbene ligands based upon a *trans*-ethanoanthracene backbone and their reaction with Rh(I) sources. Although previous chiral enetetramines have been reported by Lappert,[18a] **2** represents the first tethered enetetramine and provides a new synthetic entry into chiral bis-chelating NHC complexes. The ligands presented are representative of the numerous iterations possible with this new design. Straightforward derivatization of the carbene moiety will enable

(21) The molecular structure of **5-^{i}Pr** was also determined by X-ray diffraction. Crystal data: **5-^{i}Pr:** $C_{60}H_{68}N_4Cl_2Rh_2$, M = 1121.90, orthorhombic, space group $P2(1)2(1)2(1)$, a = 13.5851(16) Å, b = 16.976(2) Å, c = 22.353(3) Å, U = 5155.1(10) Å^3, Z = 4, D_c = 1.466 g cm^{-3}, T = 173(2) K, μ = 0.787 mm^{-1}, wR_2 = 0.0744 (11 774 independent reflections), R_1 = 0.0454 [$I > 2\sigma(I)$].

adaptation of these ligands to meet the specific demands of enantioselective catalysis. Finally, these ligands represent an alternative to current C_2-symmetric bisphosphines.

Acknowledgment. The authors thank the Camille and Henry Dreyfus Foundation and the Petroleum Research Fund-G (#44063-G3) administered by the American Chemical Society, and K.A.A. wishes to thank the NSF and UF for funding the purchase of X-ray equipment.

Supporting Information Available: Text, figures, crystallographic data tables, CIF files for **1-Me**, **2**, **3**, **4**, **5-Me**, and **5-^{i}Pr**, experimental protocols, and ^{1}H and ^{13}C NMR spectra of all new compounds including 2-D NMR spectra. This material can be found free of charge via the Internet at http://pubs.acs.org.

OM700630U