A zwitterionic zirconium complex that catalyzes hydroamination of aminoalkenes at room temperature†

Kuntal Manna, Arkady Ellern and Aaron D. Sadow*

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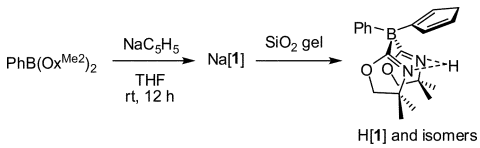
The zwitterionic cyclopentadienyl-bis(2-oxazolinyl)borate diamidozirconium(IV) complex is a precatalyst for the cyclization of aminoalkenes to five- and six-membered rings under mild conditions.

Bent-sandwich Group 4 compounds are among the most versatile of catalyst classes, mediating a range of processes involving insertion and σ-bond metathesis steps.[1] Much of their chemistry depends on three mutually adjacent frontier orbitals located in the wedge of the 14-electron Cp_2M-fragment ($Cp = C_5H_5$).[2] Modified ligands, such as the *ansa*-bis(cyclopentadienyl)[3] or mixed cyclopentadienyl-amido ligands,[4] or the incorporation of a borate in the ligand periphery,[5] have enhanced reactivity. Combining these concepts, a borate-containing, mixed Cp–L_n (L_n = donor group) ligand could provide reactive compounds by reducing the effective electron count while maintaining the critical mutually-*cis* configuration of orbitals. Herein, we report zwitterionic zirconium and hafnium diamido compounds containing such a dianionic mixed cyclopentadienyl-bis(oxazolinyl)borato ligand that are reactive precatalysts for aminoalkene hydroamination.

Two general mechanisms have been proposed for intramolecular olefin hydroamination catalyzed by Group 4 metal complexes. In a mechanism favored for cationic zirconocene alkyls and constrained-geometry zirconium catalysts,[6,7] turnover-limiting olefin insertion into a Zr–N bond gives the new C–N bond. The alternative imido mechanism,[8] proposed for bis(amidate) and phenolate-oxazoline piano-stool-type zirconium compounds,[9,10] provides the C–N bond through a [2π + 2π] cycloaddition. Regardless of the pathway, Group 4-catalyzed hydroaminations typically require elevated temperatures.[11,12] In contrast, our zwitterionic zirconium compound is active at room temperature.

Reaction of $Na[C_5H_5]$ and $PhB(Ox^{Me_2})_2$ (Ox^{Me_2} = 4,4-dimethyl-2-oxazolinyl)[13] for 12 h in THF at room temperature yields a product formulated as $Na[PhB(C_5H_5)(Ox^{Me_2})_2]$ (Na[**1**], eqn (1)). The ^{11}B NMR spectrum of the crude material in acetonitrile-d_3 contained three borate resonances (−15.4, −15.0, and −14.5 ppm). These resonances are upfield relative to the starting material $PhB(Ox^{Me_2})_2$ (−8.1 ppm, acetonitrile-d_3) that was characterized as a four-coordinate acetonitrile adduct.[13] This material was not isolated but instead was purified by column chromatography on silica gel (hexane : EtOAc : Et_3N = 12 : 7 : 1) to give $H[PhB(C_5H_5)(Ox^{Me_2})_2]$ (H[**1**]).

The isolated H[**1**] is also a mixture of three species according to ^{11}B NMR spectroscopy (−15.3, −15.6, and −16.0 ppm).

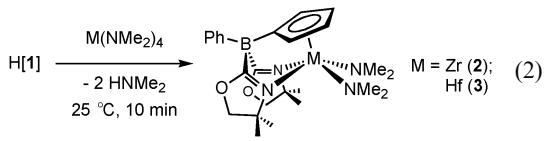


(1)

However, only one ^{15}N NMR resonance was observed at −172 ppm in a ^1H–^{15}N HBQC experiment, 45 ppm upfield of free 4,4-dimethyl-2-oxazoline (−127 ppm). In addition, only one ν_{CN} was observed in the infrared region at 1589 cm^{-1}, and free 4,4-dimethyl-2-oxazoline was not detected (ν_{CN} = 1630 cm^{-1}).[14] For comparison, in hydrogen tris-(4,4-dimethyl-2-oxazolinyl)phenylborate,[15] two ν_{CN} were observed at 1627 and 1594 cm^{-1} corresponding to non-protonated and protonated oxazoline groups, respectively. This spectroscopic evidence is consistent with both oxazoline groups interacting with a proton in H[**1**].

A related ligand based on pyrazolyl (pz), rather than oxazoline, is obtained from the redistribution of $Sm(Cp)(Tp^*)_2$ (Tp^* = $HB(3,5\text{-}Me_2pz)_3$) as part of the samarium complex $\{HB(C_5H_4)(Me_2pz)_2\}Sm(\kappa^3\text{–}Tp^*)$.[16] Also, titanium(IV) diamides coordinated by the dianionic bis(pyrrolyl)methane ligand have η^5–η^1 ground state structures and are active as intermolecular alkyne hydroamination catalysts at 75 °C.[17] Group 3 compounds containing the monoanionic ligand $[(C_5H_4)CPh_2CH(Me_2pz)_2]$ (bpzcp)[18] are isoelectronic with the cyclopentadienyl-bis(oxazolinyl)borate Group 4 compounds described here.

The isomeric mixture of H[**1**] reacts with $M(NMe_2)_4$ (M = Zr, Hf) in benzene at room temperature to give $\{PhB(C_5H_4)(Ox^{Me_2})_2\}M(NMe_2)_2$ in high isolated yield (Zr (**2**), 97.6%; Hf (**3**), 97.9%, eqn (2)). One set of diastereotopic oxazoline resonances was observed in the ^1H NMR spectrum (benzene-d_6) consistent with a C_s-symmetric species.



(2)

These oxazoline resonances (in toluene-d_8) were well resolved and are equivalent from 300 K to 190 K. No fluxionality was observed, suggesting that both oxazoline groups are

Department of Chemistry, Iowa State University and AMES Laboratory, 1605 Gilman Hall, Ames, IA, USA.
E-mail: sadow@iastate.edu; Fax: +1 515 294 0105;
Tel: +1 515 294 8069

† Electronic supplementary information (ESI) available: Procedures and characterization data for compounds **1–4**, representative kinetic data, and X-ray crystallographic data for **4**. CCDC 748394. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b918989k

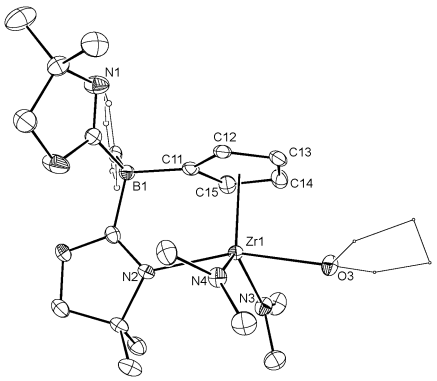


Fig. 1 ORTEP diagram of $\{PhB(C_5H_4)(Ox^{Me_2})_2\}Zr(NMe_2)_2THF$ (**4**). The THF and C_6H_5 are drawn as stick bonds, and hydrogen atoms are not shown. Zr1–C11, 2.518(2) Å; Zr1–C12, 2.492(2) Å; Zr1–C13, 2.528(2) Å; Zr1–C14, 2.569(2) Å; Zr1–C15, 2.547(2) Å, Zr1–N3, 2.045(2) Å; Zr1–N4, 2.062(1) Å; Zr1–O3, 2.414(1) Å. Cp_{cent}–Zr1–N2, 99.4°.

coordinated to the metal center. This configuration was further supported by the infrared spectra, where only one ν_{CN} band was detected (Zr: 1595; Hf: 1595 cm^{-1}, KBr). A weak peak was observed for the hafnium derivative at 1549 cm^{-1}; note that only the symmetric mode is expected to have significant intensity. A peak corresponding to uncoordinated oxazoline was not observed.

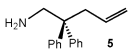
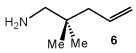
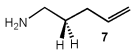
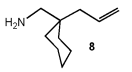
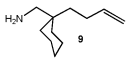
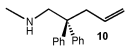
Compound **2** crystallizes as a THF adduct $\{PhB(C_5H_4)(Ox^{Me_2})_2\}Zr(NMe_2)_2THF$ (**4**) with one oxazoline coordinated to the zirconium center (Fig. 1).[19] The geometry of the complex is best described as a four-legged piano-stool. The NMe_2 ligands are transoid (N3–Zr–N4, 120.26(6)°), as are the coordinated oxazoline and THF ligands (N2–Zr1–O3, 159.40(4)°). The cyclopentadienyl ring is bonded through all five carbons, but in a twisted fashion such that the shortest distance is Zr1–C12 (2.492(2) Å) rather than Zr1–C11 (2.518(2) Å, where C11 is the carbon bonded to boron).

The room temperature ^1H NMR spectrum of **4** in toluene-d_8 was identical to a combination of the independent spectra of **2** and THF. However, at 190 K, the diastereotopic methyl and methylene signals were coalesced into broad resonances. This fluxionality is the only NMR evidence for THF coordination. Similar behavior was observed for the hafnium analog.

In contrast with **2**, the IR spectrum of **4** (KBr) contained two ν_{CN} bands: one at 1610 cm^{-1} is assigned to the non-coordinated oxazoline ring, and one at 1533 cm^{-1} is due to the bound group. Comparison of this spectrum with that of **2** further supports $(\eta^5\text{-}C_5H_4)\text{-}\kappa^2\text{-}(Ox^{Me_2})_2$ coordination in the THF-free species.

Compound **2** is a precatalyst for the conversion of aminoalkenes to corresponding pyrrolidenes and a piperidine (see Table 1). As is typical, the cyclization efficiency increases as the substrates' substituents increase in size (Ph (**5**) > Me (**6**) > H (**7**)). However, there are several unusual features of this catalysis. First, the reaction proceeds at room temperature, which is uncommon for Group 4-catalyzed hydroaminations. Second, THF only moderately inhibits the conversion and the apparent turnover rate (compare entries 1 *vs.* 2 and 5 *vs.* 6). Third, long reaction times only slightly increase the conversion, and the apparent turnover rate (N_t) decreases with increasing

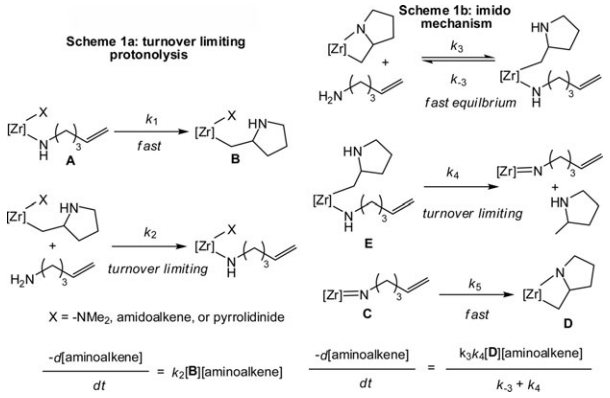
Table 1 Hydroamination/cyclization of aminoalkenes

	Cat	Substrate	Solvent	Time/h	Conversion (yield)[a]	N_t/h^{-1}[b]
1	**2**		C_6D_6	11	90 (84)	0.82
2	**2**		THF	11	68	0.62
3	**2**		THF	23	87	0.38
4	**3**		C_6D_6	24	29	0.12
5	**2**		C_6D_6	11	85	0.77
6	**2**		THF	11	72	0.65
7	**2**		C_6D_6	17	59	0.35
8	**2**		C_6D_6	33	62	0.18
9	**2**		THF	11	29	0.26
10	**2**		C_6D_6	11	92 (87)	0.84
11	**2**		C_6D_6	11	87 (80)	0.79
12	**2**		C_6D_6	48	0	0

Conditions: 10% catalyst loading. Temperature, 23 °C.[a] Conversion (%) was determined by ^1H NMR spectroscopy. Isolated yield (%) from reactions in C_6H_6. [b] Since second-order kinetics were observed, N_t is time dependent and was calculated by $\{[substrate]_0 - [substrate]_t\}/\{t \times [catalyst]\}$.

time (*i.e.*, N_t is time dependent). This rate dependence on time contrasts typical lanthanide-mediated aminoalkene cyclization kinetics, which show zero-order dependence on substrate concentration. Attempts to increase conversion or improve the rate by heating the reaction mixture were unsuccessful. Finally, the formation of cyclohexyl-substituted piperidine and pyrrolidene are catalyzed at similar rates (*cf.* Table 1, entries 10 and 11). For comparison, the seemingly related $[(C_5H_4)SiMe_2N\text{-}t\text{-}Bu]Zr(NMe_2)_2$ catalyzes the cyclization of 2,2-dimethyl-4-penten-1-amine with a turnover rate of 0.07 h^{-1} at 100 °C (an insertion mechanism was proposed).[7] The 4-legged piano-stool compound $Cp^*(L)Zr(NMe_2)_2$ (L = silicyloxazolinato) forms a more active catalyst (N_t = 2.35 h^{-1}) although temperatures of 90 °C are employed (imido mechanism was proposed).[10]

The mechanism of **2**-catalyzed hydroamination/cyclization was investigated more closely to better understand these unusual features. $HNMe_2$ is observed by ^1H NMR spectroscopy upon addition of the aminoalkene substrate to **2**. Although the active catalyst is not directly observed, it is formed at room temperature within 5 min after addition of aminoalkene **5** to **2**, based on the appearance of 2-methyl-4,4-diphenylpyrrolidine product in the ^1H NMR spectrum of the reaction mixture. For two half-lives, plots of ln[**5**] *vs.* time are linear (see ESI† for kinetic data), and this is consistent with first-order dependence on substrate concentration. After two half-lives, however, the reaction rate significantly decreases, and first-order plots are not linear over three half-lives. Independent verification of the substrate order is provided by the method of initial rates.[20] In these experiments, the initial substrate concentration was varied over several runs while catalyst concentration was kept constant; the initial rate (d[**5**]/dt) was then determined for each run. A plot of ln(initial rate) *vs.* ln[**5**] is linear, and a slope of 0.94 verifies first-order dependence on [**5**].[20] Likely, the severe rate decrease after two half-lives results from product inhibition, as the least hindered



Scheme 1

product shows the poorest conversion. Two experiments were performed to support this idea: (1) the reaction rate is slowed by addition of product, and (2) addition of more substrate results in further conversion. A plot of k_{obs} *vs.* [**2**] (ranging from 6.8 to 40 mM) reveals a linear dependence on [**2**], providing the empirical rate law: $-d[\mathbf{5}]/dt = k'[\mathbf{5}][\mathbf{2}]$ ($k' = 2.0(3) \times 10^{-3}$ M^{-1} s^{-1}). A large primary kinetic isotope effect ($k_H/k_D = 5.4$) is determined by comparison of k' obtained from **5** and **5**-d_2 substrates. Interestingly, the rate constant for cyclization of the less hindered substrate **6** is almost three times larger ($k' = 5.67(5) \times 10^{-3}$ M^{-1} s^{-1}) than the rate constant for **5**. This difference is not reflected in the 'turnover rate' since the product from **6** shows greater catalyst inhibition than the product from **5**.

Two mechanisms are consistent with the experimental rate law. The first (Scheme 1a) involves rapid intramolecular insertion followed by turnover-limiting protonolysis. This overall sequence is similar to the well-established insertion mechanism for hydroamination/cyclization,[21] with the important distinction that the relative rate constants for the insertion and protonolysis steps in the classic mechanism are reversed in our mechanism. This turnover-limiting protonolysis mechanism is also consistent with a large kinetic isotope effect and rapid catalyst initiation. However, facile alkene insertion into a Zr–N bond is unusual, as is the requirement that protonolysis be slower than alkene insertion.

A second mechanism involves reversible substrate coordination, turnover-limiting α-abstraction to form a zirconium imido intermediate, and subsequent rapid [2π + 2π] cycloaddition for C–N bond formation (Scheme 1b).[9,10] The large isotope effect is consistent with this mechanism, as α-NH abstraction reactions have significant isotope effects.[22] This mechanism is also consistent with the observation that a secondary amine substrate does not undergo cyclization.

Attempts to isolate or trap a zirconium imido in this system have not yet been successful. However, the lack of reactivity of the secondary amine **9** is unlikely to be due to steric hindrance. In addition, related four-legged piano-stool zirconium compounds are proposed to catalyze hydroamination/cyclization through an imido pathway.[10] For these reasons, we favor the imido mechanism of Scheme 1b. These catalytic reactions show that this zwitterionic zirconium compound is activated toward hydroamination/cyclization of aminoalkenes. Given the general versatility of bent-sandwich compounds in catalysis and the enhanced reactivity demonstrated here, [$PhB(C_5H_4)$-$(Ox^{Me_2})_2$]ZrX_2-type compounds may offer new possibilities in catalytic chemistry.

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19 Crystal data for $C_{29}H_{45}BN_4O_3Zr$ (**4**), $M = 599.72$, monoclinic, $P2_1/n$, $a = 12.7494(5)$, $b = 17.2023(7)$, $c = 13.5397(5)$ Å, $\beta = 93.952(1)^\circ$, $V = 2962.5(2)$ Å^3, $T = 123(2)$ K, $Z = 4$, 31 553 reflections collected, 6824 independent reflections ($R_{int} = 0.0382$), $R = 0.0274$, w$R_2 = 0.681$ [$I > 2\sigma(I)$], $R = 0.0357$, w$R_2 = 0.0732$ (all reflections).
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