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Balance between Metal and Ligand Reduction in Diiminepyridine Complexes of Ti

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Supporting Information

ABSTRACT: Reaction of the diiminepyridine ligand ^{Et}DIP (2,6-Et₂-C₆H₃N=CMe)₂C₅H₃N) with TiCl₃(THF)₃ gave the corresponding Ti(III) complex (^{Et}DIP)TiCl₃ (**1**). Reduction of **1** with 1 equiv of K⁺C₈ produced the formally Ti(II) complex (^{Et}DIP)TiCl₂ (**2**). From this, (^{Et}DIP)TiClR complexes (R = Me (**3a**), Me₃SiCH₂ (**3b**), Ph (**3c**)) were obtained by addition of 1 equiv of RLi. Similarly, dialkyl complexes (^{Et}DIP)TiR₂ (R = Me (**4a**), Me₃SiCH₂ (**4b**)) were obtained with 2 equiv of RLi. All new complexes except **3b** were characterized by single-crystal X-ray diffraction. EPR studies indicate that complex **1** is best regarded as a true Ti(III) complex with an “innocent” DIP ligand. Complexes **2–4** are all diamagnetic. In contrast to DIP complexes of the late transition metals Fe and Co, the new complexes **2–4** show strong upfield ¹H NMR shifts for the pyridine β and γ protons caused by transfer of negative charge to the DIP ligand. On the basis of this and the C=N and C_{imine}–C_{py} bond lengths, a description involving Ti(IV) and a dianionic ligand seems most appropriate, and DFT calculations support this interpretation. This means that reduction of Ti(III) complex **1** results in oxidation of the metal center to Ti(IV). VT-NMR studies of **4a** suggest a small and temperature-dependent thermal population of a triplet state, and indeed calculations indicate that **4a** has the lowest singlet–triplet energy difference of the systems studied.

INTRODUCTION

Next to the choice of a metal itself, the metal oxidation state is one of the key determinants of reactivity of metal complexes. Low-valent metals may undergo oxidative addition, and higher-valent metals tend toward reductive elimination and/or Lewis acid catalysis. The introduction of redox-active ligands has blurred this simple picture. In a combination of a metal with such a ligand, the formal oxidation state of the metal may be deceptive. In addition, the ligand may serve as an electron reservoir, supporting chemistry that would not happen with the same metal and a redox-innocent ligand. Finally, the combination of redox-active ligands and non-noble metals has been reported to lead to chemistry more typical of noble-metal catalysis.^{1–3}

Within this context, the diiminepyridine (DIP) ligand (Scheme 1) occupies a pre-eminent position. It stabilizes

metals in low formal oxidation states, often in electronic structures that have ligand-centered electrons antiferromagnetically coupled to metal-centered electrons. The DIP ligand has been documented to accept up to three electrons in its π^* orbitals,⁴ and once it has accepted one or more electrons, it preferentially stabilizes lower-spin states of the metal, such as intermediate-spin Fe(II),⁵ low-spin Mn(III),⁶ and low-spin Co(II).^{7,8}

The ligand derives much of its popularity from the formation of active polymerization catalysts in combination with Fe and Co, as originally reported by Brookhart⁹ and Gibson.¹⁰ Since then, combinations with virtually all redox-active first-row transition metals have been studied extensively: for just a few references see V,^{11,12} Cr,^{13,14} Mn,^{15–19} Fe,^{20–32} Co,^{8,33–36} Ni,^{37–39} and Cu.^{40–42} Many of these studies have focused on ligand-centered redox activity and/or olefin polymerization (the latter reported not only for Fe and Co but also for Cr¹³ and V^{11,43} complexes). Surprisingly, only a single paper mentions the combination of DIP with titanium. Calderazzo et al. studied Ti, Zr, and Hf complexes of ^HDIP and ^{iPr}DIP with an emphasis on activity in olefin polymerization.⁴⁴ The reaction of DIP with TiCl₄ was reported to give the cationic Ti(IV)

Scheme 1. ^RDIP Ligand

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species $[(\text{DIP})\text{TiCl}_3]^+$. Heating $[(^{\text{iPr}}\text{DIP})\text{TiCl}_3]^+\text{Cl}^-$ in toluene resulted in spontaneous reduction to the neutral Ti(III) complex $(^{\text{iPr}}\text{DIP})\text{TiCl}_3$ (characterized by XRD and IR), which could also be prepared directly from $^{\text{iPr}}\text{DIP}$ and $\text{TiCl}_3(\text{THF})_3$. In addition, they reported the formation of diamagnetic $(^{\text{iPr}}\text{DIP})\text{TiCl}_2$ (characterized by elemental analysis and IR) from $^{\text{iPr}}\text{DIP}$ and $\text{TiCl}_2(\text{THF})_2$. The authors do not appear to have considered the possible noninnocence of the DIP ligand in these formally Ti(III) and Ti(II) complexes. In contrast, recent work by the group of Panda⁴⁵ on Ti complexes of the potentially redox active α -diimine (ADI) ligand indicates that in $(\text{ADI})\text{TiCl}_2$, $(\text{ADI})\text{Ti}(\text{Cp})\text{Cl}$, and $(\text{ADI})\text{Ti}(\text{Cp})\text{CH}_2\text{SiMe}_3$ the σ^2, π -bound ADI ligand is in the doubly reduced state. In the present work, we report the synthesis and characterization of $(^{\text{Et}}\text{DIP})\text{Ti}$ halide and alkyl complexes and probe the spectroscopic oxidation state of the metal using NMR, EPR, XRD, XPS, and computational methods. The $^{\text{Et}}\text{DIP}$ ligand was chosen because it offers a nice compromise in terms of solubility and steric shielding of the metal center.

RESULTS AND DISCUSSION

Syntheses. Syntheses of formally Ti(III) and Ti(II) complexes are summarized in Scheme 2. The “spontaneous

Scheme 2. Synthesis of Ti(III) and Ti(II) Complexes

reduction” route toward $(^{\text{Et}}\text{DIP})\text{TiCl}_3$ (**1**) was found to be rather messy. In contrast, the reaction of $^{\text{Et}}\text{DIP}$ with TiCl_3 in

THF cleanly yields **1**. This dark green compound has low solubility in common organic solvents. X-ray-quality crystals were obtained by layering THF solutions of $^{\text{Et}}\text{DIP}$ and TiCl_3 .

Reduction of **1** with KC_8 in THF afforded $(^{\text{Et}}\text{DIP})\text{TiCl}_2$ (**2**) in high yield. This complex shows much higher solubility in common solvents, giving deep green solutions. Alkylation of **2** with 1 equiv of RLi ($\text{R} = \text{Me}$, Me_3SiCH_2 , Ph) produced the mixed alkyl–chloro complexes $(^{\text{Et}}\text{DIP})\text{Ti}(\text{R})\text{Cl}$ (**3a–c**). Use of 2 equiv of MeLi or $\text{Me}_3\text{SiCH}_2\text{Li}$ gave the dialkyls $(^{\text{Et}}\text{DIP})\text{TiR}_2$ (**4a,b**); curiously, reaction with 2 equiv or an excess of PhLi did not yield any isolable $(^{\text{Et}}\text{DIP})\text{TiPh}_2$, producing instead mixtures of uncharacterized compounds. Attempted syntheses of mono- and dialkyl compounds bearing β -hydrogens were unsuccessful. All of the aforementioned formally Ti(II) complexes (**2**, **3a–c**, **4a,b**) are dark green solids, air-sensitive but thermally rather stable. For example, $(^{\text{Et}}\text{DIP})\text{TiMe}_2$ survives prolonged heating at 85°C .

The above synthetic procedures represent the standard approach to low-valent iminepyridine complexes. However, alternative routes have been reported, such as deprotonation/oxidation of coordinated picolylamine ligands.^{46,47}

X-ray Structural Characterization. The molecular structures of all new compounds except **3b**⁴⁸ were determined by single-crystal X-ray diffraction. Unfortunately, we find that complexes of $^{\text{Et}}\text{DIP}$ have a high tendency to crystallize with disorder in the orientation of one or more Et substituents, reducing the precision of the resulting geometric parameters. Selected bond lengths are collected in Table 1.

The structure of **1** (Figure 1) shows a distorted-octahedral environment around Ti, with three rather different Ti–Cl bond

Figure 1. Molecular structure of **1**. Hydrogens and ethyl CH_3 carbons are omitted for clarity.

lengths (2.3418(12), 2.2547(13), and 2.4154(11) Å); one of the chlorides is bent back over the DIP ligand ($\angle\text{N2–Ti–Cl41}$

Table 1. Selected Bond Lengths (Å) for $(^{\text{Et}}\text{DIP})\text{Ti}$ Complexes

	1	2	3a	3c	4a	4b
Ti–N1	2.202(3)	2.107(4)	2.040(2)	2.155(2)	2.059(2)	2.119(2)
Ti–N2	2.160(3)	1.971(4)	1.972(2)	1.971(2)	1.990(2)	2.014(2)
Ti–N3	2.219(3)	2.094(6)	2.139(2)	2.041(2)	2.122(3)	2.089(3)
Ti–X41	2.415(1)	2.279(2)	2.109(3)	2.102(2)	2.111(3)	2.078(3)
Ti–X51	2.254(1)	2.268(2)	2.2998(9)	2.2977(8)	2.109(4)	2.093(3)
Ti–X61	2.342(1)					
N1–C12	1.298(5)	1.325(7)	1.360(3)	1.317(3)	1.355(4)	1.347(4)
C12–C13	1.459(6)	1.411(7)	1.398(3)	1.429(4)	1.386(4)	1.418(4)
C17–C18	1.471(6)	1.41(1)	1.424(3)	1.392(3)	1.421(4)	1.404(4)
C18–N3	1.298(4)	1.333(8)	1.326(3)	1.369(4)	1.339(4)	1.355(4)

= 79.38(8)°). These deformations are very similar to those reported by Calderazzo⁴⁴ for (iPrDIP)TiCl₃ (2.344(1), 2.298(1), 2.429(1) Å; 80.79(9)°). The three independent molecules in the unit cell of (iPrDIP)ScCl₃⁵ also show such a “bent-back” chloride, with a longer M–Cl bond; therefore, this deformation is likely due to sterics rather than caused by the presence of a single 3d electron.

The formally Ti(II) complexes **2–4** all have a distorted-square-pyramidal Ti environment. The structures of **2**, **3c**, and **4b** are shown in Figures 2–4, respectively, and those of **3a** and

Figure 2. Molecular structure of **2**. Hydrogens and ethyl CH₃ carbons are omitted for clarity.

Figure 3. Molecular structure of **3c**. Hydrogens and ethyl CH₃ carbons are omitted for clarity.

Figure 4. Molecular structure of **4b**. Hydrogens and ethyl CH₃ carbons are omitted for clarity.

4a (very similar to **2**) are provided in the Figures S4 and S7 in the Supporting Information. In the mixed alkyl–chloro complexes **3a,c**, the alkyl group occupies the apical position, which might be due to trans influence. The highest possible symmetry for **3c** is C_s, but we find that the phenyl group (C41–C46) has rotated out of the potential mirror plane through Ti1, N2, Cl51, and C41, with ∠(Ti1N2Cl51C41), (C41–C46) =

22.5°. In the highly sterically hindered complex **4b**, the apical Me₃SiCH₂ group is folded back toward the pyridine ring of the DIP ligand, while the equatorial alkyl group is stretched out away from the DIP ligand.

Bond lengths have been used as indicators of the amount of charge absorbed by the DIP ligand.^{6,8} Electron transfer from metal to ligand results in the population of low-lying ligand π* orbitals which are C=N antibonding but C_{imine}–C_{py} bonding, resulting in elongation of the former and contraction of the latter bonds. Table 2 compares relevant bond length changes.

Table 2. DIP Ligand Bond Length Changes (Å)^a

	av C=N	av C _{imine} –C _{py}	av deform ^c
0e transfer ^b	1.280	1.493	(0)
1e transfer ^b	1.330	1.437	0.053
2e transfer ^b	1.337	1.425	0.063
1	1.298	1.465	0.023
(iPrDIP)TiCl ₃ ⁴⁴	1.286	1.478	0.011
2	1.329	1.411	0.066
3a	1.343	1.411	0.073
3c	1.343	1.411	0.073
4a	1.347	1.404	0.078
4b	1.351	1.411	0.077
av over 2–4	1.343	1.409	0.073

^aFor a complete list of reference data used, see Table S2 in the Supporting Information. ^bSee text for explanation. ^cSee eq 1.

Reference bond lengths were obtained as follows from structures in the Cambridge Structural Database⁴⁹ (see the Supporting Information for details):

For no electron transfer (0e): averages over several (DIP)MnCl₂ and (DIP)CoCl₂ complexes

For 1e transfer: averages over several (DIP)Co(alkyl) complexes

For 2e transfer: averages over several (DIP)Fe(N₂), (DIP)Fe(N₂)₂, and [(DIP)Fe(N₂)₂](μ-N₂) complexes

As an aggregate measure we use Δ*d*, the average of elongations of the C=N bonds and contractions of the C_{imine}–C_{py} bonds relative to their 0e reference values:

$$\Delta d = \frac{1}{2} [(d_{\text{C=N}}(\text{av}) - d_{\text{C=N}}^{\text{0e}}(\text{av})) + (d_{\text{imine-py}}^{\text{0e}}(\text{av}) - d_{\text{imine-py}}(\text{av}))] \quad (1)$$

The average Δ*d*(1e) for the reference set of 1e transfer molecules is 0.053 Å. The Δ*d* values for our complex **1** (0.023 Å) and Calderazzo's (iPrDIP)TiCl₃ (0.011 Å) are much smaller, indicating little electron transfer in these complexes and supporting a description involving Ti(III) bound to a neutral DIP ligand. The average Δ*d*(2e) for the set of reference 2e transfer molecules (0.063 Å) is much smaller than twice the value of Δ*d*(1e), suggesting that bond length changes may not be linear in the amount of electron transfer.

In any case, the average Δ*d* value for our complexes **2–4** (0.073 Å) is larger than the Δ*d*(2e) reference, which we take as indicating the presence of Ti(IV) bound to a dianionic DIP ligand, i.e. a dominant contribution of resonance structures **B** and **C** in eq 2, rather than the perhaps to be expected Ti(III)–ligand radical anion combination.

One final comment on bond lengths involves the (lack of) symmetry of the DIP skeleton. While complexes **1**, **2**, and **4b** each show two basically identical C=N and C_{im}–C_{py} bonds,

those in **3a,c** differ considerably, with rms left–right differences of 0.03–0.04 Å. This could be interpreted as partial localization of the negative charge on the ligand: i.e., unequal contributions of structures **B** and **C**. However, all complexes show left–right equivalence in solution on the NMR time scale, and calculations (vide infra) consistently produce symmetric structures. We therefore attribute the considerable asymmetry in the solid state of **3a,c** (and the lesser asymmetry of **4a**) to packing forces, which would mean that the energy difference between symmetric and more localized structures is very small.⁵⁰

One problem with the analysis of DIP ligand bond lengths is that the changes due to electron transfer are not very large, while at the same time the presence of Et group disorder in virtually all of our ^{Et}DIP complexes reduces the precision with which skeleton bond lengths are determined. Ti–Cl bond lengths suffer less from this problem. For a few closely related Ti Cp–phosphinimide complexes, Stephan⁵¹ reported Ti–Cl bond lengths of ~2.31 Å for Ti(IV) and ~2.38 Å for Ti(III). There are not many Ti(II) halides, but a reasonable range appears to be 2.4–2.5 Å.^{52,53} The observed range of 2.27–2.30 Å for complexes **2** and **3** is highly suggestive of a Ti(IV) assignment. For complex **1** the situation is less clear, since the three Ti–Cl bonds have rather different lengths; the average of 2.34 Å suggests a situation somewhere between Ti(III) and Ti(IV). Ti–C bond lengths are also sensitive to the oxidation state of the metal. Our Ti–C bond lengths for **3** and **4** (2.08–2.11 Å) are much shorter than the Ti–Me bond of 2.219(2) Å in the true Ti(II) complex Ti(CH₃)₂(dmpe)₂⁵⁴ and closer to the bond length observed for e.g. Ti(IV) in (BDMP)TiBr·(CH₂CM₂Ph) (2.121(7) Å).⁵⁵

EPR of 1. The reported magnetic moments for (^HDIP)TiCl₃ (1.67 μ_B) and (^{iPr}DIP)TiCl₃ (1.72 μ_B)⁴⁴ establish the presence of a single unpaired electron but do not provide information on the location (ligand or metal) of that electron. The low solubility of **1** in most solvents presented a problem for EPR measurements: only CH₂Cl₂ dissolved enough to allow recording of meaningful X-band EPR spectra, but this solvent often gives a poor glass on cooling, leading to aggregation behavior and preferred orientation effects of the paramagnetic solutes. Indeed, in pure CH₂Cl₂ the EPR spectrum of **1** is very broad and asymmetric. In an attempt to reduce such preferred orientation/aggregation effects, we added [ⁿBu₄N]PF₆ to the solution. The EPR spectrum of this frozen mixture (Figure 5) is indeed sharper but otherwise shows peak positions overall identical with those of the spectrum in pure CH₂Cl₂. Some aggregation/preferred orientation effects remain, and as a result a satisfactory simulation of the experimental spectrum could only be obtained by assuming the presence of two species (ratio ~1:4) with very similar *g* tensors but differing widely in their line width parameters (Table 3). This behavior is best ascribed to remaining “bad glass” effects and probably does not mean that there are really two different EPR-active species in the sample.

The rhombicity of the *g* tensor and the significant deviations of the *g* values from *g*_e (2.0023) demonstrate that the unpaired

Figure 5. Experimental and simulated X-band EPR spectra of **1** recorded at 20 K using a frozen solution in CH₂Cl₂ containing ~0.1 M [ⁿBu₄N]PF₆. Experimental parameters: frequency 9.362511 GHz, modulation amplitude 4 G, microwave power 0.632 mW. The simulated spectrum was obtained using the parameters shown in Table 3.

Table 3. EPR Parameters Used To Simulate the Spectrum in Figure 5

	<i>g</i> _x	<i>g</i> _y	<i>g</i> _z	<i>W</i> _x	<i>W</i> _y	<i>W</i> _z
“species 1” (80%)	1.938	1.855	1.761	49	51	152
“species 2” (20%)	1.958	1.875	1.778	15	25	102

electron is substantially or even predominantly metal centered, suggesting a formulation of **1** as (^{Et}DIP⁽⁰⁾)Ti^{III}Cl₃. Computational studies are in reasonable agreement, although the calculated *g* values are all slightly higher than the observed values, indicating a somewhat more extensive delocalization of spin density over the DIP ligand in these calculations (for details see the Supporting Information).

NMR Studies. Complexes **2–4** all show fairly similar NMR spectra. Resonances are mostly sharp and in the normal 0–10 ppm range, indicative of diamagnetic complexes.

Reported ¹H chemical shifts for the backbone of DIP complexes show remarkable variations in chemical shift as a function of the metal fragment bound to it (Table 4).

DIP complexes of formally Co(I), which are proposed to actually contain low-spin Co(II) antiferromagnetically coupled

Table 4. Observed (Calculated^a) ¹H NMR Shifts (ppm) for DIP Ligand Backbone

complex	py H3/5	py H4	imine Me
2	5.99 (6.58)	5.11 (5.77)	1.79 (1.54)
3a	5.87 (6.52)	5.19 (5.62)	1.30 (1.47)
3b	5.99 (6.42)	5.29 (5.54)	1.34 (1.42)
3c	5.58 (6.11)	5.27 (5.18)	1.07 (1.20)
4a	5.08 (6.30)	4.57 (5.35)	1.57 (1.42)
4b	5.81 (6.45)	5.12 (5.51)	1.32 (1.41)
(^{Et} DIP)Co(CH ₂ SiMe ₃) ₅ ⁵⁶	7.72	10.05	−1.09
(^{iPr} DIP)Fe(N ₂) ₂ ⁵	10.11	2.58	13.61

^aCalculated values are for analogous ^{Me}DIP complexes. For a more detailed comparison of observed calculated ¹H and ¹³C NMR parameters, see Figures S26–S32 in the Supporting Information.

to a ligand-centered electron, show a strong low-field shift for pyridine H4 (9.5–10.5 ppm), a normal shift for H3/5, and a high-field shift for the imine methyl group (−1 to 0 ppm).⁷ In contrast, (¹PrDIP)Fe(N₂)₂, which likely contains intermediate-spin Fe(II) antiferromagnetically coupled to two ligand-centered electrons, shows an extreme high-field shift for H4 and low-field shifts for H3/5 and the imine methyl groups.⁵ These shifts cannot be explained by a simple increase or decrease of ligand-centered electron density and are most likely related to spin-admixture or thermally populated triplet states.

In contrast, the values observed for **2–4** are much more normal and are reproduced by DFT calculations (for details see the Supporting Information). Both H3/5 and H4 display a considerable high-field shift consistent with the presence of a reduced, negatively charged ligand, as represented by structures **B** and **C** in eq 2. High-field shifts indicating negative charge accumulation on the pyridine ring have also been reported for 2e reduced monoiminepyridine ligands.⁵⁷

While the square-pyramidal solid-state structure of **2** has at most C_s symmetry, the solution NMR data show effective C_{2v} symmetry, implying rapid exchange of apical and equatorial chlorides (eq 3).

The spectra of **3a–c** exhibit effective C_s symmetry, implying that the alkyl groups do not exchange between the two apical positions. The spectra of **4a,b** are temperature-dependent, but in rather different ways. Complex **4b** shows strongly broadened resonances for the alkyl groups. When the temperature is lowered to −50 °C, the signals decoalesce to show two inequivalent Me₃SiCH₂ groups; heating to +80 °C resulted in coalescence to a single set of CH₂SiMe₃ resonances and effective C_{2v} symmetry. An Eyring plot based on simulation of the VT-NMR line shape of the SiMe₃ groups produced the activation parameters ΔH[‡] = 10.7(3) kcal/mol and ΔS[‡] = −3(1) cal/(mol K), confirming the intramolecular nature of the exchange. Evidently the “inversion” of the SP structure is much more difficult for **4b** than for **2**. This is perhaps not surprising: in addition to a simple canting of the TiR₂ unit, 180° rotations around both Ti–CH₂ bonds are required (see Figure 4 and eq 4), and these should be strongly hindered by the ligand side

arms. Similar dynamic behavior with barriers of ~10 kcal/mol has been observed for (^{Me}DIP)Fe(CH₂SiMe₃)₂ and two closely related iron dialkyls,²⁴ as well as for (¹PrDIP)Zn(CH₂C₆H₅)₂,⁵⁸ suggesting similar steric factors at work.

The room-temperature spectrum of **4a** shows a broad resonance for the imine methyl groups. However, cooling does not result in decoalescence, nor does heating cause any sharpening (Figure 6). Rather, the chemical shift of the imine methyl signal changes by about 1.5 ppm over the temperature range from −60 to +80 °C. In addition, the line width of this resonance increases with temperature, from ~10 Hz at −60 °C to ~50 Hz at +70 °C. The pyridine H4 and H3/5 signals also

shift and broaden, while the CH₂(Et) signals shift but show little broadening. Curiously, the Me(Ti) resonance changes little with temperature and remains a singlet. Over the whole temperature range, the ligand signals are consistent with effective C_{2v} symmetry.⁵⁹ Thus, we believe the most reasonable explanation for the imine methyl broadening is the presence of a small (<1%) and temperature-dependent amount of triplet (^{Et}DIP)TiMe₂ in equilibrium with the dominant singlet species, similar to e.g. the situation reported by Autschbach for bis-semiquinone complexes of ruthenium.⁶⁰

XPS. X-ray photoelectron spectroscopy is one of the most direct techniques for establishing the oxidation state of a metal atom. While the exact binding energies of core orbitals vary somewhat depending on the precise nature of the ligands around the metal, different oxidation states are typically associated with distinct ranges of the binding energy. Table 5 presents the Ti 2p_{3/2} binding energies of the complexes measured, together with relevant reference data. Parent complex **1** has a binding energy of 457.7 eV typical of Ti(III) complexes such as Ti₂O₃ and TiCl₃.^{61–63} Reduction of **1** by removal of a chloride leads to complex **2**, which might be expected to have a Ti(II) center. However, its observed binding energy is 458.7 eV, typical of Ti(IV)^{61–64} rather than Ti(II), which would be observed around 454.7 eV.^{64,65} Alkylation to give **3** or **4** results in a very small decrease of the Ti 2p binding energy, which remains in the range typical of Ti(IV). The XPS data thus agree with the formulation of **1** as containing (DIP⁰)Ti^{III} and indicate the “more reduced” complexes **2–4** actually contain Ti in a *higher* oxidation state: (DIP^{2−})Ti^{IV}.

Computational Studies. Complexes **1'–4'**, containing the ^{Me}DIP model ligand instead of ^{Et}DIP, were studied by DFT methods (Turbomole, TPSSh functional, def-TZVP basis set), starting from the solid-state structures but replacing the original DIP Et groups by Me groups. The final optimized ligand geometries agree well with the X-ray structures, be it that the optimized structures for **2'–4'** are all left–right symmetric within error margins. A spin density plot for complex **1'** (Figure 7) shows that the single unpaired electron is mostly concentrated on Ti, but with evident delocalization to the ligand π system, consistent with the X-ray, EPR, and XPS results.

For structures **2'–4'**, broken-symmetry solutions were explored, but with very few exceptions (vide infra) the SCF calculations converged to closed-shell solutions. This is in marked contrast to low-valent Co and Fe DIP complexes, where broken-symmetry solutions are often preferred. Electronically and geometrically, **2'–4'** are all rather similar. The HOMO has little Ti character and basically corresponds to one of the two DIP π* orbitals, while the LUMO is the second π* orbital; Figure 8 shows these orbitals for **4a'**. The singlet–triplet energy difference is rather small and varies somewhat with the computational method used. In agreement with NMR data mentioned earlier, **4a'** is predicted to have the smallest singlet–triplet separation of the studied complexes. In fact, TPSSh/def-TZVP seems to overestimate the stability of the triplet, making it 0.1 kcal/mol *more* stable than the singlet, while the NMR data for **4a** (clearly mostly diamagnetic) indicate the triplet to be ~2–3 kcal/mol *less* stable.

Triplet **4a'** is predicted to prefer a trigonal-bipyramidal (TBP) C_{2v} geometry, unlike the square-pyramidal (SP) C_s structure preferred by the singlet. The path for apical/equatorial exchange of Me groups in singlet **4a'** was briefly investigated (eq 5). At the SP geometry, a closed-shell solution

Figure 6. ^1H VT-NMR spectra for complex **4a** in toluene- d_8 (the black asterisk indicates toluene).

Table 5. Ti $2p_{3/2}$ Binding Energies from XPS

complex	binding energy (eV)
TiO ₂ ⁶⁶	458.8
TiCl ₃ ⁶³	457.8
TiO ⁶⁵	454.7
1	457.7
2	458.7
3b	458.4
3c	458.6
4a	458.4
4b	458.4

Figure 7. Calculated spin density of **1'**.

Figure 8. (A) HOMO and (B) LUMO of singlet **4a'**.

is preferred. However, deformation toward the TBP structure costs less than 1 kcal/mol. For structures close to TBP, a broken-symmetry solution becomes lower in energy, and its energy at its optimized TBP geometry is only ~ 0.5 kcal/mol above the SP closed-shell singlet. Interestingly, the broken-

symmetry solution has the two antiferromagnetically coupled electrons occupying π^* -type SOMOs concentrated on the left and right sides of the DIP ligand (Figure 9), rather than the metal/ π^* orbital combination usually found in formally Co(I) and Fe(0) complexes.^{7,30}

Figure 9. (A) α and (B) β SOMO of C_{2v} -**4a'**.

As mentioned earlier, the difference in ligand ^1H NMR chemical shifts between our new “Ti(II)” complexes and formally low valent Co and Fe complexes is remarkable. To investigate this further, we also calculated ^1H NMR chemical shifts for **2'**–**4'** using the GIAO method. Unlike the case for low-valent Co and Fe complexes, these predictions are reasonable, including the high-field shift of the pyridine ring protons (Table 4). This means that no contributions of thermally populated or spin-admixed triplet states are needed to explain these shifts, and it is only for complex **4a** that we have any indication of a thermally populated triplet state.

Conclusions. True Ti(II) complexes are rare, and Ti(II) is a strong reductant. It is therefore not surprising that in the reported new formally low-valent Ti DIP complexes the diiminepyridine ligand is noninnocent, accepting two electrons. It seems complex **1** is perhaps closest to $(\text{DIP}^{(0)})\text{Ti}^{\text{III}}$, while **2**–**4** are probably best regarded as containing $(\text{DIP}^{2-})\text{Ti}^{\text{IV}}$. Experimental data establish a diamagnetic ground state for **2**–**4**, although the NMR data for **4a** indicate the presence of a thermally populated triplet state. Calculations indicate the presence of a low-lying triplet state for all formally Ti(II) complexes. Nevertheless, the mono- and dialkyl complexes **3** and **4** are surprisingly thermally stable, with both **4a** and **4b** surviving temperatures up to 85 °C in solution. However, alkyl derivatives bearing β -hydrogens could not be isolated, likely due to easy β -elimination.

Perhaps the most surprising outcome of this work is the observation that reduction of **1** to **2** results in oxidation of

Ti(III) to Ti(IV). The situation is somewhat analogous to the one-electron reduction of $[\text{DIP}^{(0)}]_2\text{Mn}^{\text{II}}$, which produces $[\text{DIP}^-]_2\text{Mn}^{\text{III}}$; i.e., oxidation of the metal center.^{6,67} However, this Mn case involves a spin state change at the metal (high spin to low spin), which is not possible for Ti.

EXPERIMENTAL SECTION

General Considerations. All air- and moisture-sensitive manipulations were carried out under argon using standard Schlenk techniques or in an MBraun drybox containing an atmosphere of purified nitrogen. Solvents for air- and moisture-sensitive manipulations were dried and deoxygenated using sodium/benzophenone. Benzene- d_6 and toluene- d_8 were purchased from Cambridge Isotope Laboratories, distilled from sodium/benzophenone, and stored in the drybox. $\text{TiCl}_3(\text{THF})_3$ was isolated from refluxing a mixture of $\text{TiCl}_3 \cdot \text{AlCl}_3$ in THF.³⁹ The $^{\text{Et}}\text{DIP}$ ligand was prepared according to a literature procedure.⁶⁸

^1H and ^{13}C NMR spectra were recorded at 25 °C (unless noted otherwise) on Bruker Avance 300 and 500 spectrometers. All chemical shifts are reported in ppm relative to SiMe_4 using ^1H (residual) and ^{13}C chemical shifts of the solvent as a secondary standard: C_6D_6 , 7.16 and 128.06 ppm; $\text{C}_6\text{D}_5\text{CD}_3$, 2.08 and 20.43 ppm.⁶⁹ All coupling constants are in Hz. VT-NMR spectra were simulated using gNMR.⁷⁰

Elemental analyses were performed at (1) Canadian Microanalytical Service, Delta, BC, Canada, and at (2) CENTC, University of Rochester, Rochester, NY, USA. In several cases, in particular for compounds containing Ti–C bonds, C analyses were low and irreproducible despite repeated crystallizations and the use of added oxidant for the combustion analysis. We attribute this to partial formation of Ti carbides during combustion.⁷¹ NMR spectra are provided in the Supporting Information as additional proof of purity. In addition, for complex **4a** we compared the powder X-ray diffraction pattern to that calculated from the single-crystal X-ray structure, which let us exclude the significant presence of crystalline impurities (see the Supporting Information for details).

EPR samples of $(^{\text{Et}}\text{DIP})\text{TiCl}_3$ (**1**) in a flame-dried J. Young valve EPR tube were prepared under strictly anaerobic conditions using distilled solvent and recrystallized $[\text{Bu}_4\text{N}]\text{PF}_6$. X-band EPR spectra were recorded on a Bruker EMX spectrometer (Bruker BioSpin) equipped with a He temperature control cryostat system (Oxford Instruments). Simulations of the EPR spectra were performed by iteration of the anisotropic g values and line widths using the EPR simulation program W9SEPR developed by Prof. Dr. Frank Neese.⁷²

Single crystals suitable for X-ray diffraction were either sealed in glass capillaries or coated with oil in a drybox and then quickly transferred to the goniometer head of a D8 three-circle diffractometer (equipped with a rotating-anode Mo $K\alpha$ generator, multilayer optics, and an APEX-II CCD area detector) or a Bruker D8 QUEST ECO diffractometer (equipped with a Mo $K\alpha$ X-ray tube). Preliminary data revealed the crystal system. Data collection was optimized for completeness and redundancy using the APEX3 software suite. The space group was identified, and the data were reduced using the SAINT program⁷³ and corrected for absorption using SADABS.⁷⁴ The structures were solved using direct methods (SHELXS⁷⁵) and refined by full-matrix least-squares procedures (SHELXL⁷⁵).

XPS spectra were collected on a Kratos Axis Ultra DLD XPS spectrometer in a vacuum environment with a base pressure of 10–9 Torr. Al $K\alpha$ (1486.6 eV) monochromatic X-rays at 10 mA emission current and 15 kV anode voltage were used for photoexcitation. Samples were transferred from a nitrogen glovebox to the instrument in a sealed container designed to mate with the sample loading arm of the spectrometer so that the samples were not exposed to air/moisture. A coaxial charge neutralizer was utilized to prevent buildup of charge on the samples. All spectra were collected with a fixed analyzer transmission mode. Survey scans were collected with a pass energy of 160 eV, and high-resolution scans were collected with a pass energy of 20 eV. Peak fitting of the high-resolution XPS spectra was performed using CasaXPS software (casaxps.com). All peak positions

were normalized with respect to the C 1s peak with a binding energy of 285 eV.

$(^{\text{Et}}\text{DIP})\text{TiCl}_3$ (1**).** A 100 mL Schlenk tube was charged with 2.30 g (6.20 mmol) of $\text{TiCl}_3(\text{THF})_3$, approximately 30 mL of THF, and a stirrer bar. $^{\text{Et}}\text{DIP}$ (3.96 g, 9.30 mmol) was added, and the reaction mixture was stirred for 12 h, during which the color quickly changed to green. The solid was filtered off and washed three times with 20 mL of THF. The obtained crystals were dried in vacuo, giving 3.23 g of $(^{\text{Et}}\text{DIP})\text{TiCl}_3$ (90%). Suitable single crystals for X-ray studies were obtained by careful layering (1:1) of solutions of $\text{TiCl}_3(\text{THF})_3$ and $^{\text{Et}}\text{DIP}$.

Anal. Calcd for $\text{C}_{29}\text{H}_{35}\text{N}_3\text{Cl}_3\text{Ti} \cdot \text{C}_4\text{H}_8\text{O}$: C, 60.80; H, 6.65; N, 6.45. Found (1): C, 60.38; H, 7.01; N, 6.28.

$(^{\text{Et}}\text{DIP})\text{TiCl}_2$ (2**).** A 100 mL Schlenk tube was charged with 2.27 g (3.48 mmol) of complex **1**, approximately 30 mL of THF, and a stirrer bar. KC_8 (0.47 g, 3.48 mmol) was added, and the reaction mixture was stirred for 3 days. Suspended solid was removed by centrifugation, and the solvent was removed in vacuo. The solid residue was dissolved in a few milliliters of toluene and left at –35 °C to give 1.81 g (95%) of dark green crystals suitable for X-ray crystallography.

Anal. Calcd for $\text{C}_{29}\text{H}_{35}\text{N}_3\text{Cl}_2\text{Ti}$: C, 63.98; H, 6.48; N, 7.72. Found: C, 63.74; H, 6.85; N, 7.44. ^1H NMR (toluene- d_8): δ 1.21 (12H, t, J 7.5, CH_2CH_3), 1.79 (6H, s, $\text{CH}_3\text{C}=\text{N}$), 2.4, 2.9 (4H each, m, CH_2CH_3), 5.11 (1H, t, J 7.5, py 4), 5.99 (2H, d, J 8, py 3/5), 7.14 (6H, s, Ar). $^{13}\text{C}\{^1\text{H}\}$ NMR (toluene- d_8): δ 14.3 (CH_2CH_3), 15.0 ($\text{CH}_3\text{C}=\text{N}$), 24.2 (CH_2), 123.9 (py 4), 126.5 (Ar m), 126.9 (py 3), 127.8 (Ar p), 134.9 (Ar o), 142.4, 148.8 (py 2, $\text{C}=\text{N}$), 166.6 (Ar i).

$(^{\text{Et}}\text{DIP})\text{TiCl}(\text{Me})$ (3a**).** A 100 mL Schlenk tube was charged with 0.168 g (0.308 mmol) of **2**, approximately 15 mL of toluene, and a stirrer bar. Solid MeLi (0.01 g, 0.455 mmol) was added, and the reaction mixture was stirred for 3 days. Suspended solids were removed by centrifugation, and the solvent was removed in vacuo. The solid residue was dissolved in a few milliliters of toluene and left to crystallize at –35 °C, producing 0.076 g (47%) of dark green crystals suitable for X-ray crystallography (containing one molecule of toluene of crystallization).

Anal. Calcd for $\text{C}_{30}\text{H}_{38}\text{N}_3\text{ClTi} \cdot \text{C}_7\text{H}_8$: C, 72.13; H, 7.52; N, 6.82. Found (1): C, 70.62; H, 7.66; N, 6.77. ^1H NMR (toluene- d_8): δ 0.91 (6H, t, J 7.5, CH_2CH_3), 1.30 (6H, s, $\text{CH}_3\text{C}=\text{N}$), 1.36 (6H, t, J 7.8, CH_2CH_3), 1.9, 2.0 (2H each, m, CH_2CH_3), 2.04 (3H, s, TiMe), 2.6, 3.1 (2H each, m, CH_2CH_3), 5.19 (1H, t, J 7.5, py 4), 5.87 (2H, d, J 7.5, py 3/5), 6.88 (2H, d, J 7.5, Ar m), 7.07 (2H, t, J 7.5, Ar p), 7.14 (2H, d, J 7.5, Ar m). $^{13}\text{C}\{^1\text{H}\}$ NMR (toluene- d_8): δ 14.3, 14.5 (CH_2CH_3), 14.7 ($\text{CH}_3\text{C}=\text{N}$), 23.8, 24.7 (CH_2), 64.8 (TiMe), 119.9 (py 4), 126.2, 126.4 (Ar m), 127.1 (Ar p), 128.5 (py 3), 133.1, 137.2 (Ar o), 139.6, 148.0, 160.9 (py 2, $\text{C}=\text{N}$, Ar i).

$(^{\text{Et}}\text{DIP})\text{TiCl}(\text{CH}_2\text{SiMe}_3)$ (3b**).** A 100 mL Schlenk tube was charged with 0.203 g (0.373 mmol) of **2**, 15 mL of toluene, and a stirrer bar. Solid $\text{Me}_3\text{SiCH}_2\text{Li}$ (0.0351 g, 0.373 mmol) was added, and the reaction mixture was stirred for 3 days. Suspended solids were removed by centrifugation, and the solvent was removed in vacuo. The solid residue was dissolved in a few milliliters of diisopropyl ether and layered with pentane. Crystallization at –35 °C gave 0.117 g (52%) of dark green crystals.

Anal. Calcd for $\text{C}_{33}\text{H}_{46}\text{N}_3\text{ClSiTi}$: C, 66.49; H, 7.78; N, 7.05. Found (2): C, 67.36; H, 7.39; N, 7.41. ^1H NMR (benzene- d_6): δ 0.08 (2H, s, TiCH_2), 0.74 (9H, s, SiMe_3), 1.04, 1.32 (6H each, t, J 7.5, CH_2CH_3), 1.34 (6H, s, $\text{CH}_3\text{C}=\text{N}$), 2.2, 2.3, 2.6, 3.3 (2H each, m, CH_2CH_3), 5.29 (1H, t, J 7.5, py 4), 5.99 (2H, d, J 8, py 3/5), 6.97 (2H, d, J 7.5, Ar m), 7.11 (2H, t, J 7.5 Hz, Ar p), 7.22 (2H, d, J 7.5, Ar m). $^{13}\text{C}\{^1\text{H}\}$ NMR (benzene- d_6): δ 3.3 (SiMe_3), 14.0, 14.7 (CH_2CH_3), 14.9 ($\text{CH}_3\text{C}=\text{N}$), 23.7, 24.7 (CH_2CH_3), 84.1 (TiCH_2), 119.2 (py 4), 126.1, 126.5, 127.2 (Ar m,p), 128.8 (py 3), 132.7, 137.7 (Ar o), 140.7, 148.6, 161.4 (py 2, $\text{C}=\text{N}$, Ar i).

$(^{\text{Et}}\text{DIP})\text{TiCl}(\text{Ph})$ (3c**).** A 100 mL Schlenk tube was charged with 0.215 g (0.395 mmol) of **2**, 15 mL of toluene, and a stirrer bar. Solid PhLi (0.035 g, 0.416 mmol) was added, and the reaction mixture was stirred for 4 days. Suspended solids were removed by centrifugation, and the solvent was removed in vacuo. The residue was dissolved in a few milliliters of diisopropyl ether and layered with pentane (1:5).

Crystallization at $-35\text{ }^{\circ}\text{C}$ gave 0.127 g (55%) of dark green crystals. X-ray-quality crystals were obtained from benzene.

Anal. Calcd for $\text{C}_{35}\text{H}_{40}\text{N}_3\text{ClTi}$: C, 71.73; H, 6.88; N, 7.17. Found (2): C, 68.25; H, 6.76; N, 6.94. ^1H NMR (benzene- d_6): δ 0.58 (6H, t, J 7.5, CH_2CH_3), 1.07 (6H, s, $\text{CH}_3\text{C}\equiv\text{N}$), 1.46 (4H, q, J 7.5, CH_2CH_3), 1.55 (6H, t, J 7.8, CH_2CH_3), 3.1, 3.8 (2H each, m, CH_2CH_3), 4.90 (1H, t, J 7.8, py 4), 5.58 (2H, d, J 7.5, py 3/5), 6.80 (2H, d, J 7.5 Ar m), 7.04 (2H, t, J 7.5, Ar p), 7.18 (1H, t, J 7, Ph p), 7.24 (2H, d, J 7.5, Ar m), 7.37 (2H, t, J 7.5, Ph m), 8.63 (2H, d, J 6.0, Ph o). $^{13}\text{C}\{^1\text{H}\}$ NMR (benzene- d_6): δ 13.5, 14.4 (CH_2CH_3), 14.5 ($\text{CH}_3\text{C}\equiv\text{N}$), 23.0, 25.1 (CH_2), 120.9 (py 4), 125.8, 126.5 (Ar m), 127.0 (Ph o), 127.2 (Ar p), 127.5 (Ph m), 129.3 (py 3), 130.5 (Ph p), 132.5, 137.7 (Ar o), 141.0, 147.4, 163.3 (py 2, $\text{C}\equiv\text{N}$, Ar i), 207.4 (Ph i).

($^{\text{Et}}\text{DIP}$) TiMe_2 (**4a**). A 100 mL Schlenk tube was charged with 0.548 g (1.01 mmol) of **2**, approximately 15 mL of toluene, and a stirrer bar. Solid MeLi (0.053 g, 2.41 mmol) was added, and the reaction mixture was stirred for 2 days. Suspended solids were removed by centrifugation, and the solvent was removed in vacuo. The solid residue was dissolved in a few milliliters of diethyl ether and crystallized at $-35\text{ }^{\circ}\text{C}$, giving 0.336 g (66%) of dark green crystals.

Anal. Calcd for $\text{C}_{31}\text{H}_{41}\text{N}_3\text{Ti}$: C, 73.94; H, 8.21; N, 8.34. Found (1): C, 72.69; H, 8.21; N, 8.17; (2): C, 69.63; H, 7.50; N, 7.95; (2): C, 70.67; H, 7.92; N, 8.21. ^1H NMR (toluene- d_8): δ 1.17 (12 H, t, J 7.5, CH_2CH_3), 1.38 (6H, s, TiMe_2), 1.57 (6H, br, $\text{CH}_3\text{C}\equiv\text{N}$), 2.6, 2.9 (4H each, m, CH_2CH_3), 4.57 (1H, br t, py 4), 5.08 (2H, br, py 3/5), 7.02 (6H, s, Ar). $^{13}\text{C}\{^1\text{H}\}$ NMR (toluene- d_8): δ 12.6 (br, $\text{CH}_3\text{C}\equiv\text{N}$), 14.4 (CH_2CH_3), 24.1 (CH_2), 59.8 (br, TiMe_2), 118.8 (py 4), 126.1 (Ar m), 126.6 (Ar p), 136.9 (Ar o), 144.0 (br), 146.1, 155.5 (v br) (py 2, $\text{C}\equiv\text{N}$, Ph i). Py 3 not detected.

($^{\text{Et}}\text{DIP}$) $\text{Ti}(\text{CH}_2\text{SiMe}_3)_2$ (**4b**). A 100 mL Schlenk tube was charged with 0.201 g (0.370 mmol) of **2**, 15 mL of toluene, and a stirrer bar. $\text{Me}_3\text{SiCH}_2\text{Li}$ (0.070 g, 0.740 mmol) was added, and the reaction mixture was stirred for 3 days. Suspended solids were removed by centrifugation, and the solvent was removed in vacuo. The solid residue was dissolved in a few milliliters of diisopropyl ether and left to crystallize at $-35\text{ }^{\circ}\text{C}$, giving 0.153 g (64%) of dark green crystals.

Anal. Calcd for $\text{C}_{37}\text{H}_{57}\text{N}_3\text{Si}_2\text{Ti}$: C, 68.59; H, 8.87; N, 6.49. Found (1): C, 68.04; H, 9.18; N, 6.82. ^1H NMR (toluene- d_8): δ 0.10 (18H, br s, SiMe_3), 1.21 (12H, t, J 7.5, CH_2CH_3), 1.32 (6H, s, $\text{CH}_3\text{C}\equiv\text{N}$), 2.5 (4H, m, CH_2CH_3), 2.8 (4H, br, CH_2CH_3), 5.12 (1H, t, J 7.5, py 4), 5.81 (2H, d, J 7.5, py 3/5), 7.07 (6H, s, Ar). TiCH_2 not observed. $^{13}\text{C}\{^1\text{H}\}$ NMR (toluene- d_8): δ 2.8 (SiMe_3), 13.9 (CH_2CH_3), 14.5 ($\text{CH}_3\text{C}\equiv\text{N}$), 24.2 (CH_2CH_3), 80.5 (br, TiCH_2), 118.5 (py 4), 126.3 (Ar m), 126.8 (Ar p), 127.8 (py 3), 135.8 (br, Ar o), 142.7, 148.5, 155.8 (py 2, $\text{C}\equiv\text{N}$) (Ar i). ^1H NMR (toluene- d_8 , $80\text{ }^{\circ}\text{C}$): δ 0.03 (18H, s, SiMe_3), 1.19 (12H, t, J 7.3, CH_2CH_3), 1.36 (4H, br s, TiCH_2), 1.42 (6H, s, $\text{CH}_3\text{C}\equiv\text{N}$), 2.5 (4 H, m, CH_2CH_3), 2.7 (4H, CH_2CH_3), 5.19 (1H, t, J 7.0, py 4), 5.89 (2H, d, J 7.0, py 3/5), 7.07 (6H, s, Ar). ^1H NMR (toluene- d_8 , $-50\text{ }^{\circ}\text{C}$): δ -0.35 (9H, s, SiMe_3), 0.07 (2H, s, TiCH_2), 0.85 (9H, s, SiMe_3), 1.18 (12H, br s, CH_2CH_3 and $\text{CH}_3\text{C}\equiv\text{N}$), 1.28 (6H, br s, CH_2CH_3), 2.4 (2H, br m, CH_2CH_3), 2.5 (4H, br m, CH_2CH_3), 2.82 (2H, s, TiCH_2), 3.3 (2H, br, CH_2CH_3), 5.02 (1H, t, J 7.8, py 4), 5.62 (2H, d, J 7.5, py 3/5), 7.1 (6H, m, Ar).

Computational Details. For EPR studies, geometry optimizations of ($^{\text{Et}}\text{DIP}$) TiCl_3 (**1**) were carried out with the Turbomole program package⁷⁶ coupled to the PQS Baker optimizer^{77,78} via the BOpt package,⁷⁹ at the b3-lyp^{80–82}/def2-TZVP^{83,84} level. The structure was characterized by a vibrational analysis (no imaginary frequencies). EPR parameters^{85,86} were calculated with the ADF2013^{87–90} program system using the B3LYP functional with the ZORA/TZ2P basis sets supplied with the program (all electron, core double- ζ , valence triple- ζ , double polarized basis set on all atoms), using the coordinates from the X-ray structure or structures optimized in Turbomole as inputs (unrestricted SPINORBIT ZORA COLLINER calculations for the SOC corrected HFI tensors and spin polarization corrected g tensors). EPR parameters were also calculated with ORCA⁹¹ using the B3LYP functional and the def2-TZVP^{83,84} basis set (NORI, SOCType 3, SOCFlags 1,2,3,1), again using the X-ray geometry or the geometry obtained by geometry optimization using Turbomole, giving results almost identical with those for ADF.

For examination of the SP-TBP path for **4a'**, as well as prediction of NMR data, geometry optimizations for **1'**–**4'** were performed with Turbomole⁷⁶ (V6.3) coupled to the PQS Baker optimizer^{77,78} at the TPSSh⁹²/def-TZVP⁸³ level. Vibrational analyses were used to confirm the nature of the stationary points (no imaginary frequencies). Free energies were obtained by combining electronic energy, enthalpy, and entropy corrections (298 K, entropy scaled by 0.67^{93,94}) with dispersion corrections calculated using DFT-D3 (options “-func tpssh -zero”).⁹⁵ NMR chemical shifts (TPSSh functional, GIAO method,^{96,97} IGLO-II basis set⁹⁸) were calculated using Gaussian 09.⁹⁹ MO and spin density plots were generated with the program Molden.¹⁰⁰

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.7b00239.

Crystallographic and spectroscopic details and computational results (PDF)

Cartesian coordinates of optimized structures (XYZ)

Accession Codes

CCDC 1545713–1545718 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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