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A Remote Lewis Acid Trigger Dramatically Accelerates Biaryl Reductive Elimination from a Platinum Complex

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Supporting Information

ABSTRACT: A strategy for the control of electron density at a metal center is reported, which uses a remote chemical switch involving second-sphere Lewis acid binding that modulates electron density in the first coordination sphere. Binding of the Lewis acid $B(C_6F_5)_3$ at remote nitrogen positions of a bipyrazine−diarylplatinum(II) complex accelerates biaryl reductive elimination by a factor of 64,000.

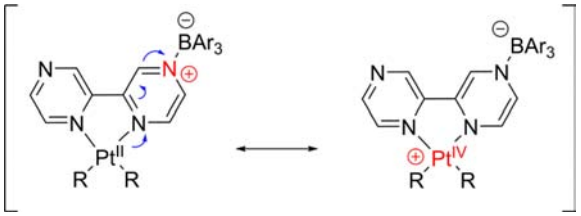
Biological catalysts utilize steric and electronic modifications to attain a remarkable degree of substrate specificity. One mechanism by which enzymes finely tune reactivity is through allosteric regulation, in which the enzyme responds to the presence of a distant activator that induces conformational changes to alter enzyme activity.[1] The operation of a chemical switching mechanism enables the active site to be protected in a stable resting state, which is converted to a more reactive form during catalysis. This allows many biological systems to be active only when a triggering signal is present, thus protecting them from decomposition.

Although tuning reactivity via chemical triggers is common in biological systems, there are currently few analogues for synthetic catalysts.[2] In particular, examples involving electronic triggers are rare. One reported strategy involves coordination of tris(pentafluorophenyl)borane, $B(C_6F_5)_3$, to carbonyl- and imine-containing nickel(II) complexes to activate these species toward ethylene polymerization catalysis.[3−5] Placement of the Lewis acid binding site remote from the reactive metal center allowed for electronic modifications without direct alteration of the coordination environment. Addition of the Lewis acid led to a 3-fold increase in polymerization activity for these systems.

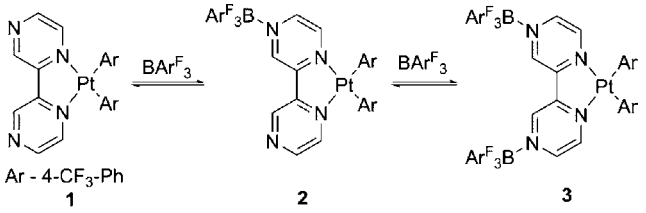
Herein, we report the synthesis and borane binding studies of platinum−bipyrazine (bpyz) complexes, as well as mechanistic studies of their biaryl reductive elimination. The para-arrangement of nitrogens featured in bpyz was envisioned to allow borane binding with formation of a zwitterionic complex having a significant resonance contributor that may be described as an electrophilic platinum(IV) species (Scheme 1). Because Lewis acid binding occurs at a remote ligand site, differences in the activity observed between borane-free and -bound complexes should enable the role of electrophilicity on reactivity to be evaluated.

A bipyrazine−diarylplatinum complex (bpyz)Pt(4-CF_3-Ph)$_2$ (**1**) was prepared by treatment of Pt(4-CF_3−Ph)$_2$(SEt_2)$_2$ with bpyz. Complex **1** reacted with variable amounts of $B(C_6F_5)_3$ in benzene to generate mono- or bis-borane adducts **2** and **3** (Scheme 2). Borane adduct formation resulted in dramatic color changes from red (**1**), to green (**2**), to brown (**3**). In the presence of 1 equiv of $B(C_6F_5)_3$, roughly equal amounts of **1**, **2**, and **3** were observed (34%, 32%, and 34%, respectively), whereas with 2 equiv of $B(C_6F_5)_3$, the product distribution changed to 3% **1**, 4% **2**, and 93% **3**. To test for the reversibility of borane coordination, isolated **3** was treated with an excess of 4-dimethylaminopyridine (DMAP), resulting in regeneration of **1** and formation of the DMAP−$B(C_6F_5)_3$ adduct (by ^{1}H and ^{19}F NMR spectroscopy).

Scheme 1



Scheme 2



Comparisons of ^{1}H and ^{195}Pt NMR data for **1** and **3** suggest a substantial impact of Lewis acid binding on electron density at the platinum center. The ^{1}H NMR resonance for H-3 of the pyrazine ring shifts from 8.01 ppm for **1** to 8.68 ppm for **3** (Figure 1). This downfield shift is consistent with coordinated $B(C_6F_5)_3$ groups withdrawing electron density from the pyrazine rings. A gradual change in ^{195}Pt chemical shift was also observed between **1** (δ = −3197 ppm), **2** (−2654 ppm), and **3** (−2070 ppm), suggesting an increase in electron deficiency upon $B(C_6F_5)_3$ coordination.[6] The ^{19}F NMR separation of para and meta resonances of the $B(C_6F_5)_3$

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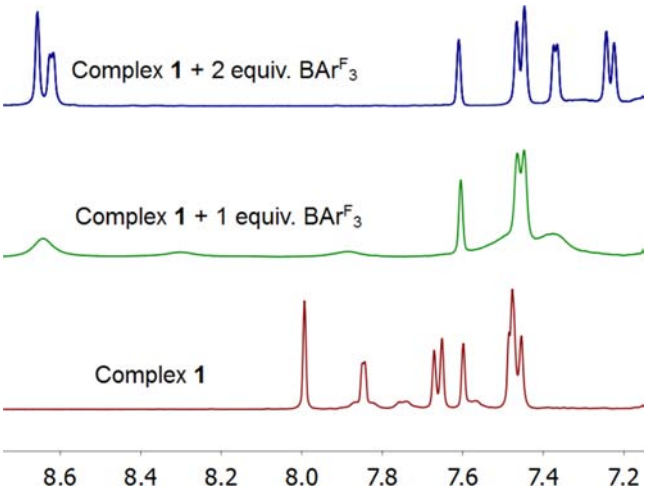
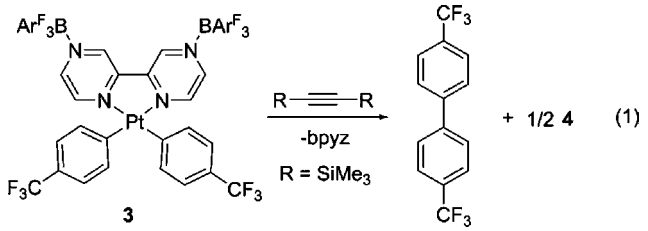


Figure 1. ^{1}H NMR spectra of **1** with added $B(C_6F_5)_3$, recorded in toluene-d_8 at 23 °C with a 1,3,5-tris(trifluoromethyl)benzene internal standard (δ = 7.61 ppm).

fragments in **3** is 8.5 ppm, consistent with an anionic four-coordinate geometry at boron.[7]

To probe the influence of borane binding on reactivity, reductive elimination studies were targeted, since group 10 metals have been shown to be highly useful catalysts for carbon−carbon coupling reactions.[8−10] Reductive elimination rates are dependent both on the nature of the transition metal, and the steric and electronic properties of the ancillary and reacting ligands.[11] Although the activity of many complexes toward reductive elimination has been attributed to electron deficiency at the metal center, few detailed studies have directly probed the role of this property on reactivity. For example, it has been shown that fluorinated phosphine ligands promote reductive elimination at platinum.[12,13] However, in such investigations, the steric environment of the platinum center is inevitably altered upon ligand modification.

In the presence of 2 or more equiv of bis(trimethylsilyl)-acetylene (BTMSA), the bis-borane adduct **3** was found to undergo quantitative biaryl reductive elimination at 45 °C (eq 1). This is a remarkably low temperature for platinum biaryl



reductive elimination, which requires temperatures above 90 °C for bis-phosphine systems.[12−14] In contrast, previous studies of diaryl(2,2′-bipyridine)platinum complexes demonstrated two consecutive roll-over metalations of the bipyridine ligand at 150 °C, along with generation of 2 equiv of Ar−H, rather than biphenyl formation.[15] In the current work, after reductive elimination from **3**, the bpyz ligand dissociates from platinum as a bis-borane adduct, yielding a platinum alkyne complex, $[Pt_2(\mu\text{-}Me_3SiCCSiMe_3)(Me_3SiCCSiMe_3)_2]$ (**4**).[16,17] Analogous reactivity is observed with other internal alkynes, such as diphenylacetylene. Attempts to induce reductive elimination with other neutral donors, such as internal alkenes or phosphines, were unsuccessful.[18]

To investigate the mechanism of reductive elimination, the reaction order in each reagent was determined by monitoring ^{19}F NMR spectra in situ. At 45 °C in *p*-xylene, reaction of **1** with 2 equiv of $B(C_6F_5)_3$ formed **3** as the exclusive platinum species. The disappearance of **3** and concomitant formation of 4,4′-bis(trifluoromethyl)-1,1′-biphenyl proceeded with clean first-order kinetics, and no intermediates were detected by ^{19}F NMR spectroscopy (Figure S2 in Supporting Information [SI]).

The slope of the plot of $\ln(k_{obs})$ vs ln[BTMSA] measured between 0.14 and 0.59 M BTMSA demonstrates that the reaction is first-order in BTMSA (Figure 2).[19] Previously,

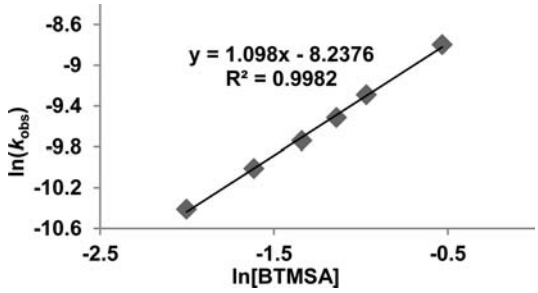


Figure 2. Plot of $\ln(k_{obs})$ vs ln[BTMSA], indicating first-order behavior.

diphosphine−nickel complexes have been observed to undergo sp^2−sp^3 reductive elimination via an associative mechanism in the presence of free phosphine.[20] In contrast, biphenyl reductive elimination from diphosphine−platinum complexes in the presence of diphenylacetylene was shown to proceed without prior alkyne association.[13]

To probe the influence of the Lewis acid on reductive elimination, the concentration of $B(C_6F_5)_3$ was varied. In the presence of 2 equiv of $B(C_6F_5)_3$, a rate constant of $k_{obs} = 1.74 \pm 0.04 \times 10^{-4}$ M·s^{-1} was determined. Doubling the concentration of $B(C_6F_5)_3$ had, within error, no effect on the observed rate constant ($k_{obs} = 1.78 \times 10^{-4}$ M·s^{-1}), suggesting that reductive elimination occurs with both equivalents of $B(C_6F_5)_3$ still bound to the bpyz ligand. A decrease in rate with added $B(C_6F_5)_3$ present would be expected if borane dissociation occurred prior to C−C bond formation.

To verify that borane binding does not induce bpyz ligand dissociation prior to reductive elimination, experiments were performed in the presence of excess free bpyz. Identical reaction rates were observed in the presence or absence of 2 equiv of free bpyz relative to platinum ($k_{obs} = 1.78 \times 10^{-4}$ M·s^{-1}), suggesting that bpyz dissociation does not occur before the rate-determining step.

The mechanism presented in Scheme 3 is consistent with the observed kinetic data. Coordination of alkyne to **3** generates a five-coordinate platinum complex. Next, biaryl coupling expels a bpyzPt−(η^2-alkyne) adduct, from which displacement of bpyz by another equivalent of alkyne leads ultimately to **4**.

To determine the rate acceleration due to borane coordination, control experiments were performed in the absence of borane (eq 2). Biaryl reductive elimination was substantially slower under these conditions, requiring heating above 100 °C to observe any biaryl formation. In the absence of borane, the reaction of **1** exhibited first-order dependence on

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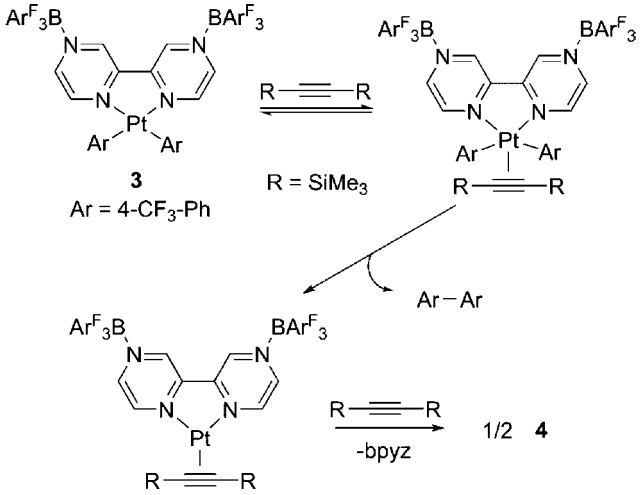
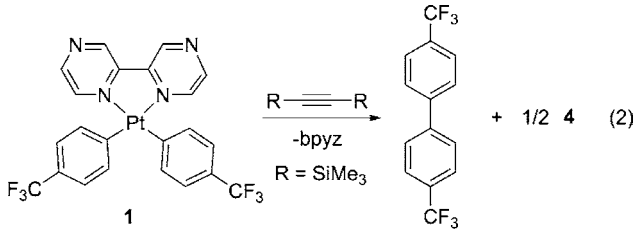
Scheme 3





[BTMSA] (Figure S5 in SI), suggesting that the reductive elimination still proceeds via a five-coordinate intermediate in this case.

An Eyring plot was constructed for the background reaction of **1** with excess BTMSA from 110−150 °C without borane present (Figure 3). From the temperature dependence of the observed rate constant in the absence of borane, activation parameters of $\Delta H^{\ddagger}$ = 29.0 ± 1.3 kcal/mol and $\Delta S^{\ddagger}$ = −6.60 ± 3.2 eu were calculated. The small, negative value for $\Delta S^{\ddagger}$ is consistent with contributions from both the alkyne coordination and reductive elimination steps.

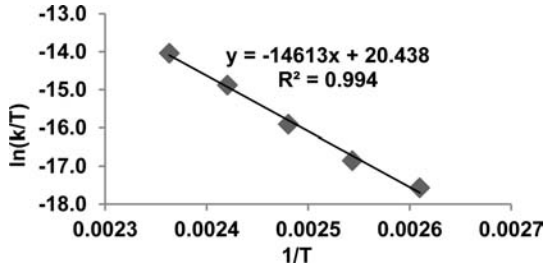


Figure 3. Eyring plot for the reaction of **1** with BTMSA.

Extrapolating to 45 °C, the temperature at which the kinetic experiments with **3** were performed, a rate constant of k_{obs} = 2.70 × 10^{-9} M·s^{-1} for the background reaction of **1** with BTMSA was estimated. Comparing the rates for the reaction of **3** or **1** with BTMSA gives a rate acceleration of ∼64,000 due to borane binding.

In conclusion, binding of Lewis acidic $B(C_6F_5)_3$ at remote nitrogen sites for a bipyrazine−diarylplatinum complex was observed. Reactions in the presence of BTMSA demonstrated facile biaryl reductive elimination, occurring in 95% yield at 45 °C. To our knowledge, this is the fastest reported biaryl reductive elimination from a platinum center, and it represents the first example using a diimine ancillary ligand system. Kinetic analysis supports a mechanism involving association of an alkyne to a bis-borane adduct and allowed calculation of a 64,000-fold rate acceleration due to borane binding. Future efforts will explore the generality of this Lewis acid binding strategy as a means for studying the role of electrophilicity in other metal-mediated reactions.

■ ASSOCIATED CONTENT

Supporting Information

Text and figures giving further experimental and spectroscopic details. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(18) No reaction was observed between **3** and cyclohexene or norbornene up to 100 °C. The reaction of **3** with triphenylphosphine showed displacement of the bpyz ligand by 2 equiv of phosphine.

(19) In the absence of alkyne, reductive elimination from **1** is sluggish, requiring heating to 170 °C for 40 h to produce 4,4′-bis(trifluoromethyl)-1,1′-biphenyl in 80% yield. Attempts to study reductive elimination from **3** were complicated due to the necessity of high reaction temperatures (>80 °C) to observe reductive elimination, and under these conditions, borane dissociation was observed. Heating **3** in the presence of excess $B(C_6F_5)_3$ (5 or 10 equiv) led to decomposition, with minimal biaryl formation (18%).

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