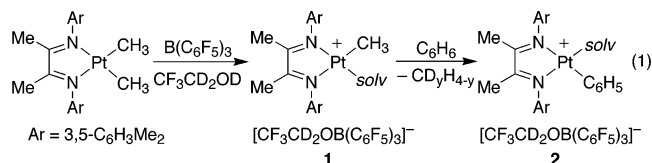


Kinetic and Thermodynamic Preferences in Aryl vs Benzylic C–H Bond Activation with Cationic Pt(II) Complexes

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The past two decades have seen a number of detailed mechanistic studies of C–H bond activation processes by transition metal complexes,¹ with the ultimate goal of new catalysts for selective hydrocarbon functionalization. Our work has focused on platinum(II) complexes, which have yielded mechanistic insight into C–H bond activation chemistry² and pointed toward promising catalysts for selective oxidation of alkanes³ and for regiospecific functionalization of complex organic molecules.⁴ The cationic Pt(II) complexes [(NN)Pt(CH₃)(CF₃CH₂OH)]⁺ (**1**, NN = ArN=C(Me)–C(Me)=NAr), obtained by protonolysis of (NN)Pt(CH₃)₂ with aqueous HBF₄, provide a particularly fertile field for mechanistic investigation.⁵ Thus prepared, however, **1** is obtained as an equilibrium mixture with the aquo complex [(NN)Pt(CH₃)(OH₂)]⁺, which is both thermodynamically favored ($K_{\text{eq}} = 10^2$ – 10^3) over, and much less reactive than, **1**. Furthermore, attempts to probe the nature of the bond activation transition state were hampered by the fact that effects of ligand variations are most strongly manifested in ground-state energies (K_{eq}).^{5e} To circumvent these limitations, we sought a water-free route to **1** and found not only the anticipated rate accelerations but also unexpected isomerizations and preferences in C–H activations of alkylbenzenes.



Solutions of the strong Lewis acid B(C₆F₅)₃ in CF₃CD₂OD exhibited a ¹⁹F NMR spectrum consistent with reversible formation of the adduct, D[(CF₃CD₂OB(C₆F₅)₃)]₂.⁶ Addition of (NN)Pt(CH₃)₂ (Ar = 3,5-dimethylphenyl) to such a solution resulted in the release of methane and quantitative formation of **1**, both produced as a mixture of two isotopomers (CH₄ and CH₃D; [(NN)Pt(CH₃)(CF₃CD₂OD)]⁺ and [(NN)Pt(CH₃D)(CF₃CD₂OD)]⁺), indicating a protonolytic route to **1** (eq 1).⁷ Addition of benzene to this solution resulted in rapid reaction of **1** to give the corresponding phenyl cation, [(NN)Pt(C₆H₅)(CF₃CD₂OD)]⁺ (**2**) and a second equivalent of methane. With excess benzene, the reaction followed clean pseudo-first-order kinetics; the calculated second-order rate constant (Table 1, entry 1) and kinetic isotope effect (KIE) were in accord with previous results for the equilibrium mixture of solvent/aquo complexes of closely related ligands.^{5e}

Previous observations on reactions of methylbenzenes with Pt(II) complexes supported an apparent strong preference for aromatic activation, which could be overridden by steric crowding.^{5c,e} Thus, **1** reacted with mesitylene exclusively by benzylic activation, to afford [(NN)Pt(CH₂C₆H₃Me₂)(CF₃CD₂OD)]⁺ (**3**). From the clean

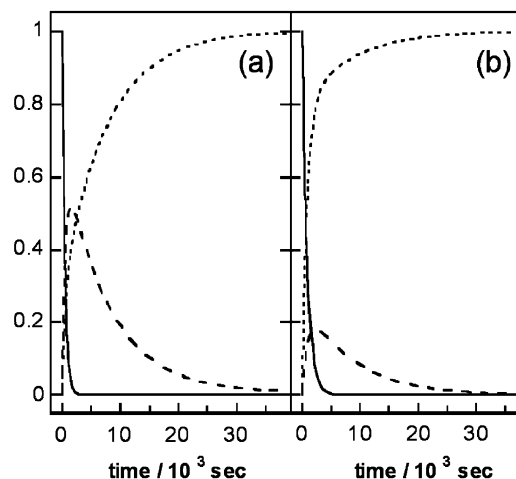


Figure 1. Plots showing the relative concentrations of platinum cations **1** (—), **4a** (---), and **4b** (···) during the reaction of **1** with (a) *p*-xylene-*h*₁₀ (0.30 M) and (b) *p*-xylene-*d*₁₀ (0.22 M) in CF₃CD₂OD at 25 °C.

Table 1. Second-Order Rate Constants for C–H Bond Activation Reactions of **1** (25 °C, CF₃CD₂OD)

entry	substrate	k_{Ar} (M ^{−1} s ^{−1})	$k_{\text{H}}/k_{\text{D}}^a$	k_{Bz} (M ^{−1} s ^{−1})	$k_{\text{H}}/k_{\text{D}}^a$
1	benzene	$1.6(2) \times 10^{-2}$	1.8 ± 0.2	na	na
2	mesitylene	na	na	$2.0(2) \times 10^{-3}$	1.1 ± 0.2
3	<i>p</i> -xylene	$4.0(13) \times 10^{-3}$	4.0 ± 1.8	$2.0(9) \times 10^{-3}$	0.8 ± 0.3

^a For perdeutero- vs *d*₀-substrate.

first-order kinetic behavior, the observed rate constant was determined to be an order of magnitude lower than that for benzene and the measured KIE was found to be essentially 1 (Table 1, entry 2).

p-Xylene reacted with **1** to give products of both aromatic (Pt-(2,5-Me₂C₆H₄), **4a**) and benzylic (Pt-(CH₂C₆H₄Me), **4b**) activation, similar to the behavior in the presence of water.^{5c,e,8} However, the initial product distribution was not stable (Figure 1). After starting complex **1** was completely consumed, **4b** continued to grow at the expense of **4a**. This conversion displayed first-order dependence on *p*-xylene concentration ($k_2 = 0.0003(1) \text{ M}^{-1} \text{ s}^{-1}$; KIE = 0.9–(2)), indicating a reaction of **4a** with *p*-xylene rather than an intramolecular isomerization process (Scheme 1). The KIEs for aromatic and benzylic C–H bond activation were quite different, as can be readily seen by comparing Figures 1a and 1b; kinetic parameters were extracted by fitting⁶ the data in Figure 1 (Table 1, entry 3). The difference in KIE for sp² and sp³ C–H bond activation was unexpected and not obviously interpretable.⁸

Toluene behaved (qualitatively) analogously: an initial mixture of benzylic and aromatic C–H activation products subsequently converted to solely the former, although the complex mixture of aryl isomers has not yet been completely analyzed. Similarly, reaction of **1** with an equimolar mixture of benzene and mesitylene afforded an initial mixture of **2** and **3** in ca. 6:1 ratio (consistent

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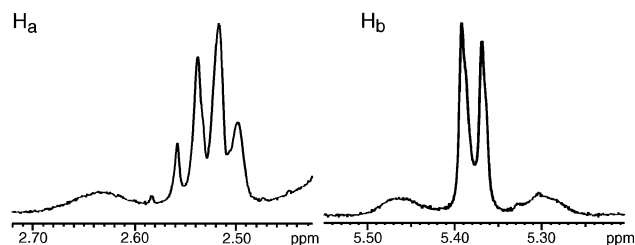
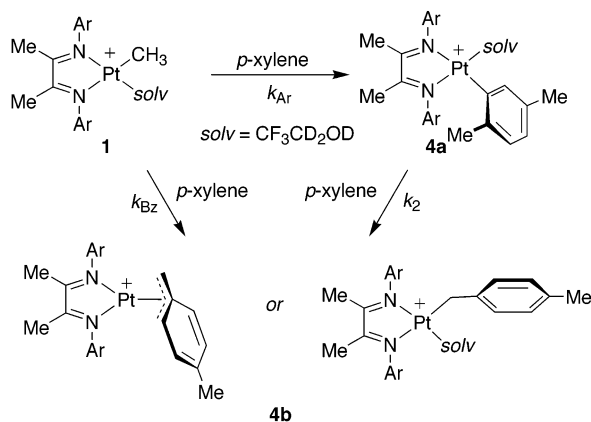


Figure 2. Diagnostic ^1H NMR spectroscopic evidence in $\text{CF}_3\text{CD}_2\text{OD}$ showing that J_{PtH} of H_a and H_b in **5** ($\text{Ar} = \text{Mes}$) supports η^3 -bonding as the thermodynamic preference for benzylic C–H activation.

Scheme 1

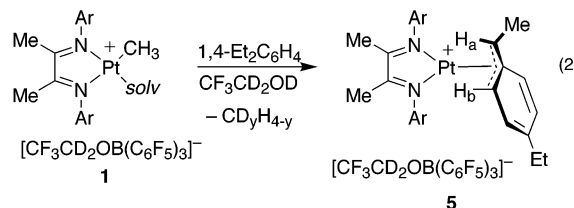


with the independently measured rate constants), which slowly ($k_{\text{obs}} \sim 10^{-5} \text{ s}^{-1}$) converted entirely⁹ to **3**.

C–H activating systems generally exhibit thermodynamic¹⁰ as well as kinetic preferences for aromatic over benzylic activation. In stark contrast, while aromatic activation here was favored kinetically, the observations indicated a decided thermodynamic preference for the products of benzylic activation. One possible explanation is that **4b** is $[(\text{NN})\text{Pt}(\eta^3\text{-CH}_2\text{C}_6\text{H}_4\text{Me})]^+$ rather than $[(\text{NN})\text{Pt}(\eta^1\text{-CH}_2\text{C}_6\text{H}_4\text{Me})(\text{CF}_3\text{CD}_2\text{OD})]^+$ where the additional contribution of η^3 -bonding might stabilize it relative to **4a**. We have been unable to crystallize **4b**, but addition of acetonitrile gave a crystallizable complex (**4b'**) whose structure is clearly $[(\text{NN})\text{Pt}(\eta^1\text{-CH}_2\text{C}_6\text{H}_4\text{Me})(\text{NCCH}_3)][\text{BF}_4]$.⁶

Evidence for the formation of a η^3 -complex was obtained when platinum methyl cation **1** was exposed to 1,4-diethylbenzene in $\text{CF}_3\text{CD}_2\text{OD}$ (eq 2). In contrast to **4**, the Pt–H coupling could be observed for both H_a and H_b ($J_{\text{PtH}} = 20$ and 30 Hz , respectively) using ^1H NMR spectroscopy. Behavior similar to that for methyl-substituted benzenes was observed with diethylbenzene: reaction with **1** also afforded aryl activation products, which were converted to η^3 -complex **5** over time.¹¹ Diagnostic Pt–H coupling of an analogous η^3 -complex was also observed when a more substituted diimine ligand ($\text{Ar} = \text{Mes}$) was employed (Figure 2). The instability of **5** (or $\text{5} \cdot \text{BF}_4$) as a solid precluded structural analysis using X-ray diffraction.

In summary, we have observed selectivity trends in the C–H bond activation of substituted benzenes using anhydrous cationic Pt(II) complexes. The thermodynamic preference for benzylic C–H



activation appears to result from stabilizing η^3 -bonding observable in **5**. Experimental and theoretical efforts are currently directed toward understanding these novel patterns for benzylic versus aromatic C–H bond activation and exploiting these selectivities in C–H bond functionalization.

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Supporting Information Available: Detailed experimental procedures, integrated rate laws for *p*-xylene reactions, proposed mechanistic interpretations, and X-ray diffraction data for **4b'** (PDF, CIF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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- (6) Experimental details, including detailed procedures, spectroscopic data, kinetics analyses and X-ray crystallographic data are provided in Supporting Material.
- (7) The alternative, methide abstraction by $\text{B}(\text{C}_6\text{F}_5)_3$, would lead to $[\text{MeB}(\text{C}_6\text{F}_5)_3]^-$ (which is stable to reaction conditions) and no deuterium incorporation into the platinum methyl cation.
- (8) Kinetic ratio of aromatic/benzylic activation here, around 2:1, is significantly different from that found for a close analogue of **1** in the presence of water, $\geq 10:1$.^{5e} The reason for this difference is not clear; (hopefully) plausible explanations for this observation as well as the unusual isotope effect behavior are offered in Supporting Information.
- (9) Under the limitations inherent to the ^1H NMR experiment, a lower limit of $K_{\text{eq}} \geq 20$ can be assigned to the equilibrium constant relating **[2]** and **[3]**.
- (10) For example, with the Tp^*RhL fragment ($\text{Tp}^* = \text{hydrotris}(3,5\text{-dimethylpyrazolyl})\text{borate}$, $\text{L} = \text{neopentyl isocyanide}$) aromatic activation of benzene is favored over benzylic activation of mesitylene by $6.6 \text{ kcal mol}^{-1}$ (Jones, W. D.; Hessel, E. T. *J. Am. Chem. Soc.* **1993**, *115*, 554–562).
- (11) While methyl C–H activation was not directly observed, exposure of **5** to deuterated alcohols caused deuterium exchange into the methyl group of the complex.

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