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Arene C−H Bond Activation and Arene Oxidative Coupling by Cationic Palladium(II) Complexes

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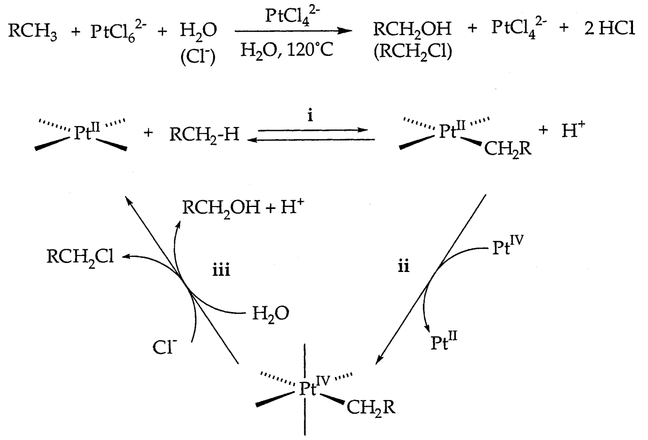
N,*N*′-Diaryl-α-diimine-ligated Pd(II) dimethyl complexes (^{tBu_2Ar}DAB^{Me})PdMe$_2$ and {$^{(CF_3)_2Ar}$-DAB^{Me}}PdMe$_2$ {^{tBu_2Ar}DAB^{Me}: ArN═C(CH$_3$)−C(CH$_3$)═NAr, Ar = 3,5-di-*tert*-butylphenyl; $^{(CF_3)_2Ar}$-DAB^{Me}: Ar = 3,5-bis(trifluoromethyl)phenyl} undergo protonolysis with HBF$_4$(aq) in trifluoroethanol (TFE) to form cationic complexes [(α-diimine)Pd(CH$_3$)(H$_2$O)][BF$_4$]. The cations activate benzene C−H bonds at room temperature. Kinetic analyses reveal trends similar to those observed for the analogous platinum complexes: the C−H activation step is rate-determining (KIE = 4.1 ± 0.5) and is inhibited by H$_2$O. The kinetic data are consistent with a mechanism in which benzene substitution proceeds by a solvent- (TFE-) assisted associative pathway. Following benzene C−H activation under 1 atm O$_2$, the products of the reaction are biphenyl and a dimeric μ-hydroxide complex, [(α-diimine)Pd(OH)]$_2$[BF$_4$]$_2$. The Pd(0) formed in the reaction is reoxidized by O$_2$ to the dimeric μ-hydroxide complex after the oxidative C−C bond formation. The regioselectivity of arene coupling was investigated with toluene and α,α,α-trifluorotoluene as substrates.

Introduction

Selective hydrocarbon functionalization has been identified as an important challenge for academic and application-based chemical research.[1] Despite 30 years of research, a catalyst that displays the requisite activity, specificity, and durability has yet to be discovered. Our approach has been to focus on elucidating the mechanism of the Shilov system (Scheme 1), in which Pt(II) salts catalyze the oxidation of alkanes to alcohols (and alkyl chlorides) by Pt(IV) at 120 °C.[2] Studies by our group and others have elucidated a three-step catalytic cycle: (i) C−H bond activation, with liberation of a proton, to produce a Pt(II)−alkyl; (ii) oxidation of the Pt(II)−alkyl by [PtCl$_6$]$^{2-}$; and (iii) nucleophilic attack by water or chloride to liberate product and regenerate the Pt(II) catalyst.[3]

Recent efforts in our group have focused on exploiting oxidation of Pt(II) complexes by O$_2$ to circumvent the use of stoichiometric Pt(IV).[4]

Scheme 1



An alternate strategy for O$_2$ utilization would employ a Pd(0)/Pd(II) redox couple to achieve the desired chemistry. Recently, oxidations of arenes to phenols[5] and of alcohols to aldehydes or ketones,[6] using Pd(II) catalysts and O$_2$ as the stoichiometric oxidant, have been reported. In addition, Stahl and co-workers demonstrated the clean reaction of [(bathocuproine)Pd(0)-(η^2-dibenzylideneacetone)] with O$_2$ to produce a Pd(II) peroxo complex, which liberates H$_2$O$_2$ upon treatment with acid.[7] If Pd(II) complexes can effect C−H activation as well, then the catalytic cycle shown in Scheme 2 could be feasible.

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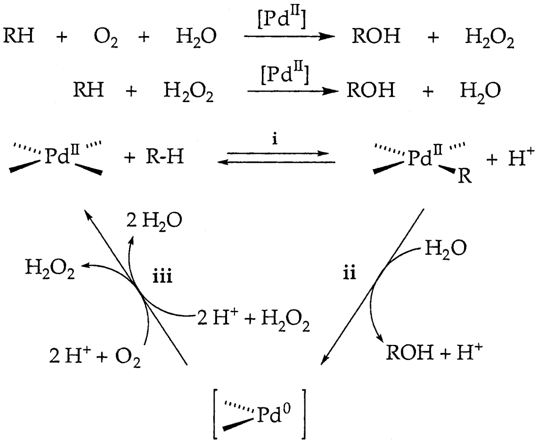
(5) (a) Jintoku, T.; Taniguchi, H.; Fujiwara, Y. *Chem. Lett.* **1987**, 1865−1868. (b) Jintoku, T.; Takaki, K.; Fujiwara, Y.; Fuchita, Y.; Hiraki, K. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 438−441.

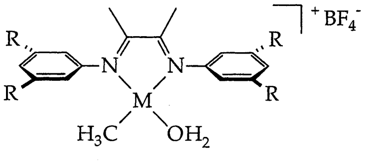
10.1021/om0303294 CCC: $25.00

Scheme 2



In this scheme, initial C−H bond activation, analogous to that observed in the Shilov system (**i**), is followed by a formal reductive elimination step (**ii**) to generate product and a Pd(0) fragment. Trapping and two-electron oxidation of the product Pd(0) complex by O_2 would then regenerate the Pd(II) catalyst (step **iii**). The H_2O_2 byproduct of the oxidation could serve as another oxidizing equivalent, or it could disproportionate to H_2O and O_2 in the presence of Pd(II) as observed in other catalytic oxidation chemistry.[8] This proposed catalytic cycle is similar to that suggested by Periana and coworkers in the Hg(II)-catalyzed oxidation of methane to methyl bisulfate by H_2SO_4.[9] Since neither Hg(II) nor Pd(II) can easily access the (IV) oxidation state (in contrast to Pt), the proposed product release involves a reductive step, followed by reoxidation to the active catalyst species.

Mechanistic studies of C−H activation by [(α-diimine)Pt(CH_3)(H_2O)][BF_4] complexes such as **1a/b** have been reported.[10] Intramolecular C−H activation by similar cationic [(α-diimine)Pd(CH_3)(L)]$^+$ complexes has been observed.[11,12] These results and the precedented reactivity of [(α-diimine)Pd(0)] complexes with O_2 (vide supra) impelled us to investigate intermolecular C−H activation by Pd(II) complexes **2a** and **2b**.



M = Pt
1a: R = CMe$_3$; **1b**: R = CF$_3$

M = Pd
2a: R = CMe$_3$; **2b**: R = CF$_3$

Results and Discussion

Synthesis of Palladium Complexes. The α-diimine ligands have been prepared previously by the formic acid-catalyzed condensation of 2,3-butanedione with the corresponding aniline in methanol.[10a,b] Dimethyl Pd(II) complexes (α-diimine)PdMe$_2$, **3a** and **3b**, were prepared by treating [(pyridazine)PdMe$_2$]$_n$[13] and (COD)PdMe$_2$[14] (COD = 1,5-cyclooctadiene), respectively, with the corresponding ligand.[11] Protonolysis of **3a/b** by HBF_4(aq) in trifluoroethanol (TFE) solvent generates the methyl aquo cations, **2a/b**. The analogous reaction of Pt(II) dimethyl complexes affords an equilibrium mixture of aquo and trifluoroethanol adducts observable by NMR; the magnitude of the equilibrium constant for different α-diimine complexes depends on the electron density at the Pt center, as assayed by CO stretching frequencies.[10a] Although we believe this aquo/solvento equilibrium is operative for **2a** or **2b** (vide infra), only one species is observed in the NMR spectra, even at low temperature or after addition of up to 50 μL of D_2O. Small chemical shift differences between the aquo and trifluoroethanol adducts of **2a/b**, and/or a low kinetic barrier for their interconversion, may account for this observation. Complexes **2a/b** are prepared in situ and have not been isolated as analytically pure solids.

Kinetics of Reactions with Benzene. Methyl cations **2a/b** react with benzene in TFE-d_3, with concomitant liberation of methane. ^{1}H NMR was used to monitor the disappearance of starting material from which rates were determined. When carried out under an atmosphere of dioxygen, these reactions proceed cleanly, affording biphenyl and palladium(II) products (vide infra). On the other hand, when **2a/b** react with benzene under an inert atmosphere (e.g., Ar), palladium metal deposition accompanies biphenyl and soluble palladium(II) product formation. The rates are not affected by ionic strength: several experiments were conducted at different D_2O concentrations with and without added [NMe_4][BF_4] with negligible change in rate constants (see Supporting Information). Hence, kinetic studies were carried out under 1 atm of O_2 without controlling ionic strength. As previously found for the analogous platinum systems,[10] the reaction is first-order in benzene, rates are decreased by added water, and $1/k_{obs}$ is linear with respect to [D_2O]/[C_6H_6] (Figure 1).[15] Reactivity falls off in the order **2a** > **2b** > **1a** > **1b** (data for **1b** was obtained at a single [D_2O]).[10a]

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[15] In the original Pt work,[10a] the [D_2O] dependence studies were conducted at 293 K. The data for **1a** in Figure 1 have been calculated using Eyring data for comparison to [D_2O] studies for **2a/b**, which were conducted at 298 K.

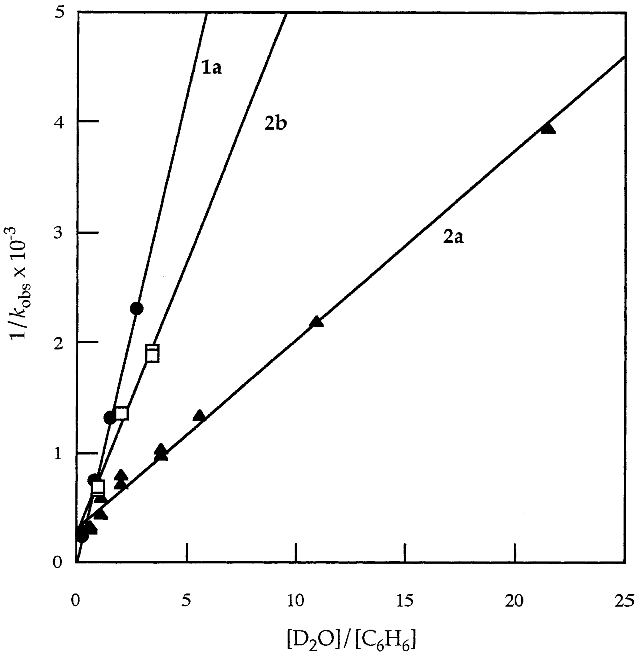
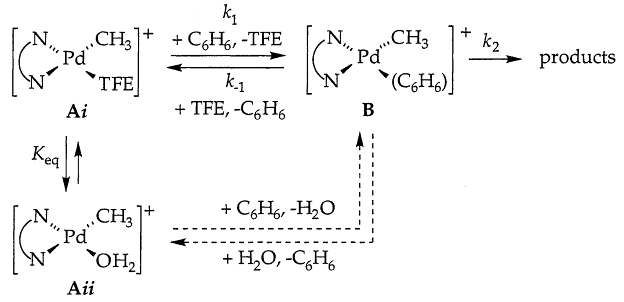


Figure 1. Plots of the reciprocal pseudo-first-order rate constants from the kinetics of reactions of [(α-diimine)M-$(CH_3)(H_2O)$][BF_4] with C_6H_6 (298 K) at varying D_2O concentrations (M = Pd, Pt).

Scheme 3



$$-\frac{d[\mathrm{Pd}]_T}{dt} = k_{obs}[\mathrm{Pd}]_T = \frac{k_2}{k_{-1}[\mathrm{TFE}] + k_2} \cdot \frac{k_1[\mathrm{TFE}][C_6H_6][\mathrm{Pd}]_T}{[\mathrm{TFE}] + K_{eq}[H_2O]}$$

The temperature dependence for the reaction between **2a** and C_6H_6 was studied over the range 1−40 °C. The activation parameters calculated from the Eyring plot ($\Delta H^\ddagger = 20 \pm 2$ kcal·mol^{-1}, $\Delta S^\ddagger = -2 \pm 6$ eu) for C_6H_6 activation are similar to the values of $\Delta H^\ddagger = 20$ kcal·mol^{-1}, $\Delta S^\ddagger = -5$ eu for **1a**.[10a,16]

The kinetic isotope effect for the reaction was calculated by separately determining the rate constants for reactions of C_6H_6 and C_6D_6 under the same conditions. The measured isotope effect is 4.1 ± 0.5. The observed primary kinetic isotope effect indicates that C−H bond cleavage (k_2, Scheme 3) is rate-determining. Unlike **1a/b**, **2a/b** reacts with C_6D_6 to liberate only CH_3D without the observance of more highly deuterated methanes. Likewise, upon protonolysis of **3a/b** in TFE-d_3, only [(CH_3)Pd(II)] cations are formed, whereas the analogous Pt dimethyl complexes are converted to both [(CH_3)Pt(II)] and [(CH_2D)Pt(II)] cations.[10a] The exclusive formation of CH_3D in the deuterolysis of **3**, or in the reaction of **2** with deuterated benzene, indicates that the kinetic barrier to methane loss is small relative to that of the deuterium scrambling processes observed for **1a/b**. Deuterium scrambling for the platinum systems has been proposed to occur by formation of both methane and arene σ-complexes which undergo more than one oxidative addition/reductive elimination sequence before methane loss.[10a,c]

Mechanism of C−H Bond Activation of Benzene by Palladium(II)−Methyl Cations. All of the observed data are consistent with the mechanism and derived rate law previously proposed for the analogous Pt systems (Scheme 3).[10a,c]

In this scheme the aquo (**A*ii***) and solvento (**A*i***) complexes are in rapid equilibrium, with benzene displacing the more weakly bound solvent ligand; direct attack of benzene on **A*ii*** to displace water is assumed to be negligible. Rate-determining C−H activation (k_2) occurs after benzene coordination (complex **B**). The accelerated rates observed for **2a** versus **2b** (ligand effects) and also **2a/b** versus **1a/b** (metal effects) can be accounted for by the magnitude of K_{eq}. Although K_{eq} cannot be measured directly for **2a/b** (vide supra), it is calculated from the slope and intercept of the $1/k_{obs}$ plot (see Supporting Information for rate law derivation). The calculated K_{eq} values for the palladium complexes are 36 for **2a** and 122 for **2b** (298 K).

The measured K_{eq} values for the platinum congeners are 430 for **1a** and 2800 for **1b** (293 K).[10a] As reflected by the measured K_{eq} values, ground state differences between the aquo (**A*ii***) and solvento (**A*i***) for a series of [(α-diimine)Pt$(CH_3)(H_2O)$][BF_4] complexes (including **1a/b**) were proposed to account for differences in C−H activation rate.[10a] The same behavior appears to be operative in the palladium cases. Thus, the more stable the aquo adduct (larger K_{eq}), the slower the C−H activation rate. The aquo adduct is more stable for the complexes with electron-withdrawing ligands (**1b** and **2b**) since the metal center is more electron-deficient, resulting in stronger bonding to the H_2O molecule. In addition, the aquo adducts are more stable for the platinum complexes **1a/b** over the palladium analogues **2a/b** due to the stronger bonding of 5d transition metals to ligands compared to 4d transition metals.[17]

The kinetic data do not provide information about the exact nature of the C−H bond-breaking step for **2a/b** (e.g., oxidative addition vs σ−bond metathesis mechanisms). For platinum, a large body of evidence has been accumulated for a Pt(IV) hydride intermediate, supporting an oxidative addition mechanism for C−H activation by **1a/b**.[10a,c,18] Because the Pd(IV) oxidation state is less readily accessible, the analogous intermediate may be less likely, although it cannot be ruled out. Canty and co-workers have structurally characterized a variety of Pd(IV) complexes, such as [(bipy)Pd$(CH_3)_3$I], obtained from oxidative addition of CH_3I to [(bipy)Pd$(CH_3)_2$].[19]

Reactivity of Palladium(II)−Methyl Cations. Unlike their platinum congeners, **2a/b** do not form stable phenyl complexes upon reaction with benzene. As noted

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[16] The reported $\Delta S^\ddagger = 5$ eu for **1a**[10a] was miscalculated. The correct value is $\Delta S^\ddagger = -5$ eu.

[17] Plots of $1/k_{obs}$ vs $[C_6H_6]/[D_2O]$ extrapolated to zero $[D_2O]$ indicate that the palladium complex **2a** reacts with benzene faster than the platinum complex **1a** by a factor of approximately 2.

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above, under an inert atmosphere reactions of **2a/b** with benzene deposit Pd(0) and produce unidentified palladium-containing byproducts and biphenyl. However, when the reaction is carried out under 1 atm of O_2, two identifiable Pd(II) species, $[(\alpha\text{-diimine})Pd(H_2O)_2][BF_4]_2$ (**4a/b**) and $[(\alpha\text{-diimine})Pd(OH)]_2[BF_4]_2$ (**5a/b**), as well as biphenyl form as the reaction proceeds. After complete reaction under O_2, the only products observed are **5a/b** and 0.5 equiv of biphenyl, with no Pd(0) deposition.[20]

Complexes **4a** and **5a** were identified by independent syntheses from the dichloride $(^{tBu2Ar}DAB^{Me})PdCl_2$ (**6a**)[21,22] and isolation of the final product, **5a**, from the C−H activation reactions. **4a** and **5a** are synthesized by adding $AgBF_4$ to a solution of **6a** in wet CH_2Cl_2/THF (10:1), as published previously. Notably, **4a** could be isolated as the sole product after the reported 3 h reaction time, but at shorter reaction times (1−2 h) mixtures of both **4a**, **5a**, and other unidentified species were observed. Dissolving the mixture in TFE-d_3, followed by addition of HBF_4(aq), results in the disappearance of the unidentified species, and only **4a** and **5a** are present in solution. Subsequent addition of HBF_4 converts all of **5a** to **4a**. **5a** is the sole product of the reaction of **2a** with benzene under O_2; the diagnostic protons on the bridging hydroxide groups were located in the ^1H NMR by evaporating the trifluoroethanol (protio solvent) and dissolving the residue in CD_2Cl_2. These protons on the bridging hydroxide groups appear at δ −3.5 ppm and disappear upon addition of D_2O. In other dinuclear (diimine)Pd(II) hydroxide complexes, these hydrogens resonate near δ −3 ppm (CD_2Cl_2).[22]

The other species observed in the mixtures of **4a** and **5a** were not identified, but are most likely related complexes. Studies of the reaction of NaOH with N-ligated $[(L_2)Pd(OH)]_2[NO_3]_2$ complexes (L_2 = bipyridine or phenanthroline) in water have shown that several species form in solution that cannot be isolated in pure form.[23] The authors postulate that a trihydroxide-bridged species may be a component of the mixture. Also, phosphine-ligated $[(BINAP)Pd(H_2O)_2][X]_2$ complexes have been isolated from the addition of AgX to the corresponding dichloride complexes (X = BF_4^- or OTf^-). Unlike **4a**, the dimers $[(BINAP)Pd(OH)]_2[X]_2$ are easily obtained from the bis(aquo) complexes by treating with 4 Å molecular sieves in acetone or treatment with 1 equiv of NaOH. When an insufficient quantity of sieves was used, a complex was isolated that was determined to be a binuclear mono-μ-hydroxo complex also having a (μ-HO···H···OH) as well.[24] These types of structures are likely related to the unidentified species observed for the α-diimine complexes in this study.

X-ray quality crystals of the hydroxide dimer complex **5b** were grown from an NMR tube reaction of **2b** and benzene (Figure 2). Details of the structure are given in the Supporting Information.

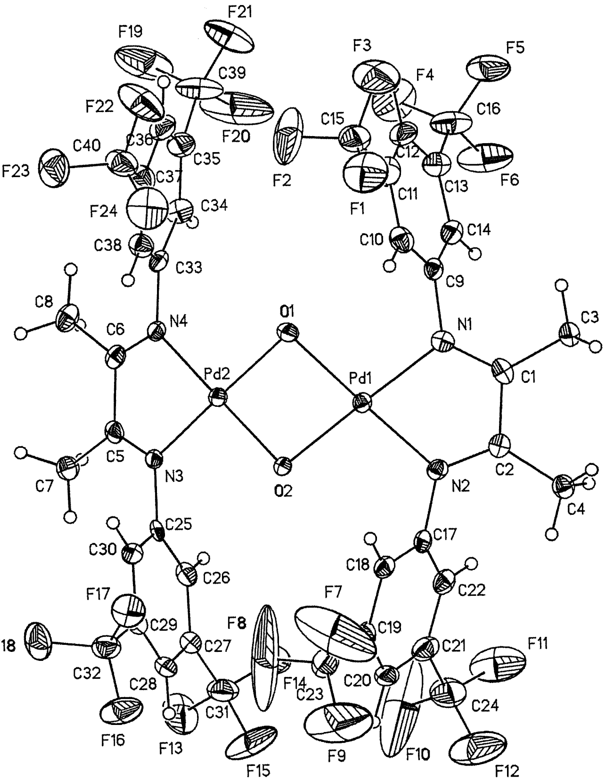

Figure 2. Molecular structure of **5b** with 50% probability ellipsoids. Hydrogen atoms and anions have been omitted. Selected bond distances (Å) and angles (deg) are as follows: Pd1−Pd2 = 2.9706, Pd1−N1 = 1.993(3), Pd1−N2 = 2.000(3), Pd1−O1 = 2.025(3), Pd1−O2 = 2.022(3), Pd2−N3 = 1.987(3), Pd2−N4 = 1.991(3), Pd2−O1 = 2.022(3), Pd2−O2 = 2.025(2), N1−Pd1−N2 = 79.03(13), N1−Pd1−O2 = 177.05(12), N1−Pd1−O1 = 99.60(12), Pd1−O1−Pd2 = 94.44(11), Pd1−O2−Pd2 = 94.45(11).

Scheme 4 illustrates the proposed reaction sequence. The species ***i***, ***ii***, and ***iii*** are unobserved postulated intermediates. First, the phenyl product, ***i***, disproportionates (possibly by phenyl group transfer) to produce ***ii*** and **4a/b**. Reductive elimination of biphenyl from ***ii*** produces a Pd(0) complex, which is reoxidized by O_2 to peroxo intermediate ***iii*** or possibly by hydrogen peroxide to **4a/b**.[7] Alternatively, hydrogen peroxide may be disproportionated rapidly.[8] Species similar to the postulated intermediates ***i*** and ***ii*** have been suggested for the intermolecular coupling of aryl ligands for $[(L_2)Pd(Ar)(solvent)][BF_4]$ (L_2 = *N*,*N*,*N′*,*N′*-tetramethylenediamine, 2,2′-bipyridine, 4,4′-dimethyl-2,2′-bipyridine; solvent = THF, acetone, acetonitrile) and other related complexes.[25]

Other potential intermediates on the pathway to arene C−C coupling have been reported for similar Pt(II) systems. Recently, Kubas[26] and Peters[27] isolated chelating bis(phosphine)Pt(II) dimer complexes that have a biphenyl unit sandwiched between the metal centers. One phenyl group of the biphenyl unit is bound

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(20) Attempts at catalytic C−C bond formation using either **4a** or **5a** gave only substoichiometric biphenyl; the bridged hydroxo and bis aquo complexes are apparently too inert to activate C−H bonds.

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(22) Kannan, S.; James, A. J.; Sharp, P. R. *Polyhedron* **2000**, *19*, 153−163.

(23) Wimmer, S.; Castan, P.; Wimmer, F. L.; Johnson, N. P. *J. Chem. Soc., Dalton Trans.* **1989**, 403−412.

(24) Fujii, A.; Hagiwara, E.; Sodeoka, M. *J. Am. Chem. Soc.* **1999**, *121*, 5450−5458.

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(26) Konze, W. V.; Scott, B. L.; Kubas, G. J. *J. Am. Chem. Soc.* **2002**, *124*, 12550−12556.

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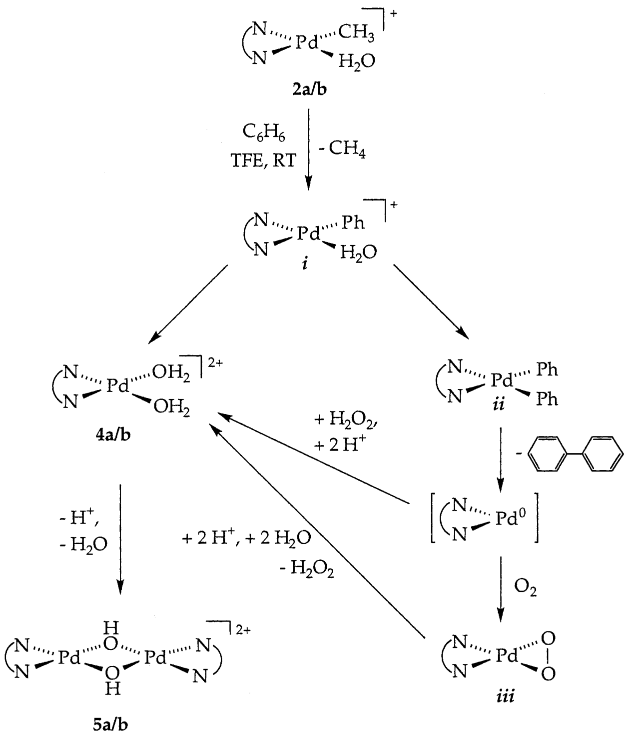
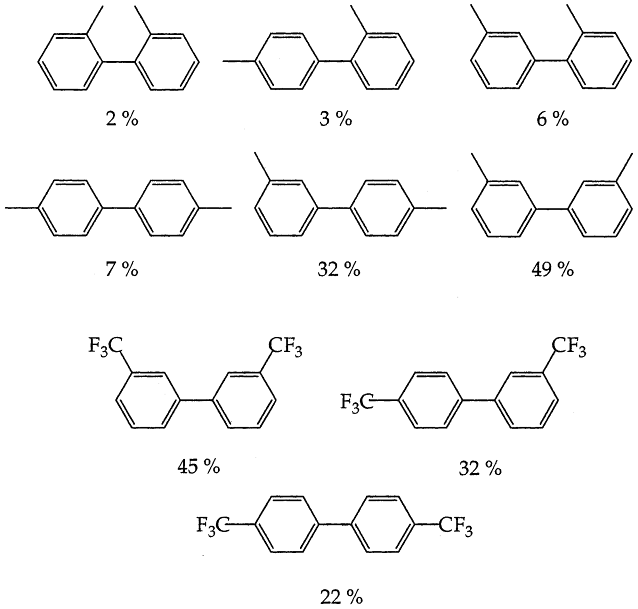
Scheme 4



as an η^3,η^3-bis-allyl to the two Pt centers, while the other remains aromatic. These unusual dimers were isolated after cationic or neutral Pt(II) phosphine complexes reacted with either benzene or toluene via C−H activation and subsequent C−C bond formation. In the Kubas system, the formally reduced biphenyl unit can be released upon oxidation with HCl to produce Pt(II) chloride dimers and H_2. These results led the authors to suggest that there is no formal redox reaction at Pt, and these dimers may resemble intermediates in Pd-mediated aryl coupling reactions. If such bis-allyl dimers are intermediates in this work, Pd acts as the oxidant for biphenyl release, since we observe Pd(0) deposition and the production of biphenyl (GC−MS) in the absence of oxidant.

Regioselectivity of Arene Coupling. Toluene and α,α,α-trifluorotoluene were investigated as substrates for arene coupling. Both substrates react with **2a** to produce mixtures of isomers as summarized in Scheme 5. Toluene reacts with **2a** faster and trifluorotoluene slower than benzene by a factor of 2 and 10, respectively. The *o*:*m*:*p* regioselectivity is approximately 1:10:7 for toluene and 0:4:5 for trifluorotoluene (after statistical correction for the number of C−H bonds).

Scheme 5



It is possible that the regioselectivity is determined during the reductive coupling from the postulated diphenyl palladium(II) intermediate, during transmetalation (Scheme 4), or during formation of a binuclear intermediate such as Kubas' $[L_4Pt_2(\mu_2\text{-}\eta^3,\eta^3\text{-}C_6H_5{-}Ph)]^{2+}$, if a different mechanism for C−C bond formation is occurring. On the other hand, if one assumes that the regioselectivity is determined by the C−H activation step, one may reconcile the observed regioselectivity as arising from a combination of steric and inductive effects of the [CH_3] and [CF_3] substituents. Thus, in the case of toluene, the palladium center more readily activates the *meta* C−H positions over the *para* C−H position, since it is the more electron-rich site inductively; the *ortho* C−H positions are sterically hindered. Similarly, for trifluorotoluene, the *para* C−H position is more reactive because it is farthest from the strongly electron-withdrawing [CF_3] group and thus most electron-rich, whereas the *ortho* C−H positions are most sterically hindered and least electron-rich. In agreement with this proposal that inductive electronic effects operate during the C−H bond activation step of these oxidative coupling reactions of arenes, the second-order rate constant for reaction **2a** with toluene (0.0124 M^{-1} s^{-1}) is significantly greater than that with α,α,α-trifluorotoluene (0.0005 M^{-1} s^{-1}).

Conclusions

Stoichiometric C−H bond activation of benzene by cationic Pd(II)−methyl complexes has been observed under mild conditions. Kinetic studies of the C−H activation step for the palladium complexes reveal that the C−H activation step is rate-determining and inhibited by H_2O. The data suggest that coordinated H_2O must be displaced by solvent (trifluoroethanol) before benzene coordination and subsequent C−H activation. The rates of C−H activation are increased by destabilizing the ground state aquo complex with relatively electron-donating ancillary ligands. Also, the ground state aquo complexes are destabilized for Pd relative to Pt, resulting in faster C−H activation rates. Finally, the barrier to methane loss for Pd is small, and in contrast with the analogous Pt systems no deuterium scrambling occurs. The Pd−phenyl product formed upon C−H activation is unstable, and biphenyl is formed as the final organic product. Pd(0) produced in the reaction is reoxidized to Pd(II) by O_2 (1 atm). Using toluene and α,α,α-trifluorotoluene as substrates results in biaryl formation with enriched *meta* and *para* substitution, respectively. Although a catalytic process remains elusive, the tandem C−H activation/O_2 activation sequence represents a promising step toward an aerobic oxidation of unactivated arenes to biaryls.

Experimental Section

General Considerations. All moisture-sensitive compounds were manipulated using standard vacuum line, Schlenk, or cannula techniques or in a drybox under a nitrogen atmosphere. Argon and dinitrogen gases were purified by passage over columns of MnO on vermiculite and activated molecular sieves. Trifluoroethanol was purchased from either Aldrich or Lancaster, purified, and dried over a mixture of $CaSO_4/NaHCO_3$, then either vacuum distilled or distilled under argon and stored over activated molecular sieves under vacuum. Trifluoroethanol-d_3 was purchased from Aldrich or Cambridge Isotopes, stored over activated molecular sieves and a small amount of $NaHCO_3$ under vacuum, and then vacuum distilled. The solvent was syringed into oven-dried screw-cap NMR tubes fitted with septa for kinetic studies. Benzene and benzene-d_6 were vacuum distilled from sodium benzophenone ketyl shortly before kinetic runs and stored over activated molecular sieves. Diethyl ether, THF, and CH_2Cl_2 were purified over an activated alumina column. 1,4-Bis(3,5-di-*tert*-butylphenyl)-2,3-dimethyl-1,4-diaza-1,3-butadiene ($^{tBu_2Ar}DAB^{Me}$),[10a] 1,4-bis(3,5-ditrifluoromethylphenyl)-2,3-dimethyl-1,4-diaza-1,3-butadiene {$^{(CF_3)_2Ar}DAB^{Me}$},[10b] [(COD)$PdMe_2$],[14] [(pyridazine)$PdMe_2]_n$,[13] ($^{tBu_2Ar}DAB^{Me}$)$PdMe_2$ (**3a**),[11] {$^{(CF_3)_2Ar}DAB^{Me}$}$PdMe_2$ (**3b**),[11] [($^{tBu_2Ar}DAB^{Me}$)Pd($H_2O)_2$][$BF_4]_2$ (**4a**),[22] [($^{tBu_2Ar}DAB^{Me}$)Pd(OH)]$_2$[$BF_4]_2$ (**5a**),[22] [$(PhCN)_2PdCl_2$],[28] and ($^{tBu_2Ar}DAB^{Me}$)$PdCl_2$ (**6a**)[21] were synthesized according to literature procedures. All other solvents and reagents were used as received without further purification.

NMR spectra were recorded on a Varian CCE 600 (^{1}H, 599.662 MHz), a Varian INOVA 500 (^{1}H, 499.852 MHz), or a Varian Mercury 300 (^{1}H, 299.8 MHz, ^{13}C, 75.4626 MHz) spectrometer. Elemental analyses were performed at Midwest MicroLab LLC.

The quantification of **5a/b** was accomplished by ^{1}H NMR integration against the residual solvent peak (CF_3CHDOD) as an internal standard. The biphenyl quantification was accomplished by GC−MS.

Bitolyl products, which are not commercially available, were synthesized by the Suzuki coupling methodology developed by Fu.[29] Bis(trifluoromethyl)biphenyl products were synthesized by oxidation of the aryl Grignard reagent by $TiCl_4$.[30]

Synthesis and Characterization of Methyl Aquo Cations (2a/b). The aquo complexes were prepared in situ by procedures described by Tilset and co-workers.[10b] Complexes **2a/b** could not be isolated as pure solids, but are stable in TFE solution for >12 h. For the kinetic studies, cations **2a/b** are generated in situ (vide infra), and the chemical shifts reported below are for solutions in TFE-d_3 in the absence of substrate.

[(^{tBu_2Ar}DAB^{Me})Pd(CH_3)(H_2O)][BF_4] (2a). ^{1}H NMR (300 MHz, TFE-d_3): δ 0.492 (s, 3H, Pd−CH_3), 1.34, 1.36 (s, 18H, C(C$H_3)_3$), 2.12, 2.19 (s, 3H, N=C−CH_3), 6.77, 6.93 (d, $^4J_{H-H}$ = 1.6 Hz, 2H, *o*-Ar−*H*), 7.49, 7.55 (t, 1H, *p*-Ar−*H*).

[{$^{(CF_3)_2Ar}$DAB^{Me}}Pd(CH_3)(H_2O)][BF_4] (2b). ^{1}H NMR (600 MHz, TFE-d_3): δ 0.511 (s, 3H, Pd−CH_3), 2.20, 2.28 (s, 3H, N=C−CH_3), 7.50, 7.58 (br s, 2H, *o*-Ar−*H*), 7.94, 7.95 (br s, 1H, *p*-Ar−*H*).

(^{tBu_2Ar}DAB^{Me})PdMe$_2$ (3a). A Schlenk flask was charged with [(pyridazine)$PdMe_2]_n$ (0.115 g, 0.530 mmol) and $^{tBu_2Ar}DAB^{Me}$ (0.256 g, 0.556 mmol). The flask was cooled to 0 °C, and Et_2O (15 mL) was transferred via cannula onto the solids. A dark red precipitate forms from the suspension of starting materials almost immediately upon solvent addition. The mixture was stirred for 2 h at 0 °C, warmed to room temperature, and filtered. The crude product was dissolved in CH_2Cl_2 (3−4 mL); the resulting solution was filtered through Celite and concentrated in vacuo, affording **3a** as a red solid (0.199 g, 63%). ^{1}H NMR (300 MHz, CD_2Cl_2): δ −0.269 (s, 6H, Pd−CH_3), 1.35 (s, 36H, C(C$H_3)_3$), 2.06 (s, 6H, N=C−CH_3), 6.73 (d, $^4J_{H-H}$ = 1.8 Hz, 4H, *o*-Ar−*H*), 7.28 (t, $^4J_{H-H}$ = 1.8 Hz, 2H, *p*-Ar−*H*). ^{13}C{^{1}H} NMR (300 MHz, CD_2Cl_2): δ −5.189 (Pd−CH$_3$), 20.16 (N=C−CH$_3$), 31.73 (C(CH$_3)_3$), 35.50 (C(CH$_3)_3$), 115.76 (*o*-Ar−*C*), 119.64 (*p*-Ar−*C*), 147.34, 151.92 (Ar−*C*), 169.84 (N=*C*−CH$_3$). Anal. Calcd for $C_{34}H_{54}N_2Pd$ (Found): C, 68.38 (68.23/68.10); H, 9.11 (8.90/8.72); N, 4.69 (4.60/4.73).

{$^{(CF_3)_2Ar}$DAB^{Me}}PdMe$_2$ (3b). A Schlenk flask was charged with [(COD)$PdMe_2$] (0.122 g, 0.500 mmol) and $^{(CF_3)_2Ar}DAB^{Me}$ (0.257 g, 0.500 mmol). The flask was cooled to 0 °C, and Et_2O (10 mL) was transferred via cannula onto the solids. A bright red precipitate formed from a clear solution, and the resulting red suspension was stirred for 1 h at 0 °C and warmed to room temperature. The red solid was filtered, washed with cold Et_2O and pentane, and dried in vacuo, affording **3b** as a red powder (0.185 g, 58%). ^{1}H NMR (300 MHz, CD_2Cl_2): δ −0.217 (s, 6H, Pd−CH_3), 2.11 (s, 6H, N=C−CH_3), 7.45 (br s, 4H, *o*-Ar−*H*), 7.84 (br s, 2H, *p*-Ar−*H*). ^{13}C{^{1}H} NMR (300 MHz, acetone-d_6): δ −4.72 (Pd−CH$_3$), 20.59 (N=C−CH$_3$), 119.50 (m, $^3J_{C-F}$ = 3.8 Hz, *p*-Ar−*C*), 122.30 (m, $^3J_{C-F}$ = 3.8 Hz, *o*-Ar−*C*), 124.10 (q, $^1J_{C-F}$ = 273 Hz, CF$_3$), 132.15 (q, $^2J_{C-F}$ = 273 Hz, *m*-Ar−*C*−CF$_3$), 149.80 (Ar−*C*), 173.96 (N=*C*−CH$_3$). Anal. Calcd for $C_{22}H_{18}F_{12}N_2Pd$ (Found): C, 40.98 (41.18/41.13); H, 2.81 (2.91/2.92); N, 4.34 (4.24/4.27).

[(^{tBu_2Ar}DAB^{Me})Pd($H_2O)_2$][$BF_4]_2$ (4a). ($^{tBu_2Ar}DAB^{Me}$)$PdCl_2$ (**6a**, 0.250 g, 0.392 mmol) was slurried in 1:1 THF/CH_2Cl_2 solution (15 mL). $AgBF_4$ (0.156 g, 0.803 mmol) was dissolved in dry THF (1 mL) and added to the reaction flask dropwise. An off-white precipitate formed immediately in a yellow solution. After 3 h, the solution was filtered through Celite and the filtrate was removed in vacuo to afford **4a** as a yellow solid (0.225 g, 74%). ^{1}H NMR (300 MHz, TFE-d_3): δ 1.37 (s, 36H, C(C$H_3)_3$), 2.27 (s, 6H, N=C−CH_3), 7.23 (d, $^4J_{H-H}$ = 1.6 Hz, 4H, *o*-Ar−*H*), 7.77 (t, $^4J_{H-H}$ = 1.6 Hz, 2H, *p*-Ar−*H*), O−*H* resonances not found due to exchange with CF$_3$CD$_2$O*D*. ^{13}C{^{1}H} NMR (300 MHz, TFE-d_3): δ 21.34 (N=C−CH$_3$), 31.99 (C(CH$_3)_3$), 37.01 (C(CH$_3)_3$), 118.42 (*o*-Ar−*C*), 127.17 (*p*-Ar−*C*), 143.91, 156.55 (Ar−*C*), 187.66 (N=*C*−CH$_3$). Anal. Calcd for $C_{32}H_{52}N_2O_2F_8B_2Pd$ (Found): C, 49.48 (49.18/49.17); H, 6.75 (6.68/6.73); N, 3.61 (3.59/3.55).

[{$^{(CF_3)_2Ar}$DAB^{Me}}Pd($H_2O)_2$][$BF_4]_2$ (4b). ^{1}H NMR (600 MHz, TFE-d_3): δ 2.19 (s, 6H, N=C−CH_3), 8.12 (br s, 4H, *o*-Ar-*H*), 8.18 (br s, 2H, *p*-Ar−*H*), O−*H* resonances not found due to exchange with CF$_3$CD$_2$O*D*.

[(^{tBu_2Ar}DAB^{Me})Pd(OH)]$_2$[$BF_4]_2$ (5a). This compound was synthesized in the same manner as **4a**, but is present in the solid isolated after a 1 h reaction time. This complex was not isolated cleanly from **4a** and other related products (see Results and Discussion section), but can be isolated cleanly from the reaction of **2a** with C_6H_6 (under 1 atm O_2). ^{1}H NMR (300 MHz, TFE-d_3): δ 1.24 (s, 72H, C(C$H_3)_3$), 2.09 (s, 12H, N=C−CH_3), 6.87 (d, $^4J_{H-H}$ = 1.6 Hz, 8H, *o*-Ar−*H*), 7.52 (t, $^4J_{H-H}$ = 1.6 Hz, 4H, *p*-Ar−*H*), O−*H* resonances not found due to exchange with CF$_3$CD$_2$O*D*. ^{1}H NMR (300 MHz, CD_2Cl_2): δ −3.51 (s, 2H, O*H*), 1.19 (s, 72H, C(C$H_3)_3$), 2.06 (s, 12H, N=C−CH_3), 6.93 (d, $^4J_{H-H}$ = 1.6 Hz, 8H, *o*-Ar−*H*), 7.34 (t, $^4J_{H-H}$ = 1.6 Hz, 4H, *p*-Ar−*H*).

[{$^{(CF_3)_2Ar}$DAB^{Me}}Pd(OH)]$_2$[$BF_4]_2$ (5b). ^{1}H NMR (600 MHz, TFE-d_3): δ 1.99 (s, 12H, N=C−CH_3), 7.61 (br s, 8H, *o*-Ar-*H*), 8.01 (br s, 4H, *p*-Ar−*H*), O−*H* resonances not found due to exchange with CF$_3$CD$_2$O*D*.

(^{tBu_2Ar}DAB^{Me})PdCl$_2$ (6a). $^{tBu_2Ar}DAB^{Me}$ (0.520 g, 1.13 mmol) was dissolved in CH_2Cl_2 (10 mL) and added to a solution of [$(PhCN)_2PdCl_2$] (0.433 g, 1.13 mmol) in CH_2Cl_2 (10 mL). An orange precipitate formed immediately. The reaction was stirred for 1−2 h. The precipitate was filtered, washed with CH_3OH and Et_2O, and dried in vacuo to afford **6a** as an orange

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(29) Littke, A. F.; Dai, C.; Fu., G. C. *J. Am. Chem. Soc.* **2000**, *122*, 4020−4028.

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powder (0.529 g, 73%). Due to the very low solubility of this complex, NMR spectroscopic data could not be collected. Anal. Calcd for $C_{32}H_{48}N_2Cl_2Pd$ (Found): C, 60.24 (60.17/60.21); H, 7.58 (7.41/7.48); N, 4.39 (4.41/4.36).

Measurement of Kinetics for C−H Bond Activation of Benzene. Dry TFE-d_3 (∼700 μL) was added via syringe to an oven-dried 5 mm thin-walled NMR tube containing approximately 0.0075 mmol of (α-diimine)$PdMe_2$ (**3a/b**). Aqueous HBF_4 (48 wt %, 1 μL, 0.00765 mmol) was added, and the mixture was shaken to form a clear, yellow solution. A predetermined amount of D_2O was then added to the tube. A screw-cap fitted with a septum was then affixed to the tube. The tube was frozen at −78 °C, evacuated with a needle, and then backfilled with 1 atm of O_2 (ultrahigh purity). After thawing, the mixture was analyzed by ^{1}H NMR to confirm clean conversion to aquo adducts **2a/b**. A predetermined amount of substrate was then added to the NMR tube, and after allowing the mixture to equilibrate to the preset temperature in the probe, disappearance of the starting material was monitored (the same observed rate constants are obtained by monitoring the appearance of biphenyl). Probe temperatures were calibrated with a methanol standard and were maintained at ±0.2 °C throughout data acquisition. The observed rate constants are calculated by curve fitting to the expression $I_t = I_f + (I_0 - I_f) \times \exp(-k_{obs}t)$, where I_t is the integration of the Pd−Me peak relative to the residual solvent peak, $CF_3C\mathit{H}DOD$. The water concentration is calculated as follows: $[H_2O] = [(1\ \mu L \times 1.4\ g{\cdot}mL^{-1} \times 52\% + y\ \mu L \times 1\ g{\cdot}mL^{-1})/18\ g{\cdot}mol^{-1}/V\ (mL)]$, where 1.4 $g{\cdot}mL^{-1}$ is the density of the aqueous HBF_4 solution, 52% is the wt % of water in this aqueous solution, y is the amount of extra water added, and 1 $g{\cdot}mL^{-1}$ is the density of water. The volume of the reaction mixture is determined as $V\ (mL) = 0.01384H - 0.006754$, where H is the solvent height in millimeters. Addition of a small amount of benzene (e.g., 15 μL) to TFE-d_3 shifts the resonances for the diimine backbone methyls by as much as 0.3 ppm and can significantly affect shimming.

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Supporting Information Available: Summary of C−H bond activation kinetic data and derivation of the rate law for Scheme 3. Details of the structure determination, tables of atomic coordinates, complete bond distances and angles, and anisotropic displacement parameters for complex **5b**. This material is available free of charge via the Internet at http://pubs.acs.org.[31]

OM0303294

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(31) Crystallographic data for **5b** (CCDC 204983) have been deposited with the Cambridge Crystallographic Data Centre as supplementary publications. These data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK.; fax: +44 1223 336033; or deposit@ccdc.cam.ac.uk). Structure factors are available electronically: e-mail: xray@caltech.edu.