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Relative Rates for the Amination of η^3-Allyl and η^3-Benzyl Complexes of Palladium

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The reaction of nucleophiles with π-ligands coordinated in an η^3-fashion is a fundamental organometallic reaction that occurs during a variety of catalytic processes.[1] The reactions of nucleophiles at allyl ligands are the most common class of these addition reactions.[2] Although reactions with η^3-benzyl complexes have been invoked as part of catalytic processes,[3] the reactions of nucleophiles with isolated benzyl complexes have been studied to a lesser extent.[4] We recently reported a series of hydroaminations of dienes and vinylarenes in which the C−N bond is likely to form by nucleophilic attack on η^3-allyl and η^3-phenethyl intermediates.[4−7] To study this step of the catalytic cycle, we have conducted synthetic and kinetic studies of the reactions of amines with isolated η^3-allyl, η^3-benzyl, and η^3-phenethyl complexes. We report the results of these studies that reveal an unexpected trend: the more common reaction of an amine with an η^3-allyl complex is slower than the less common reaction with a related η^3-benzyl complex. Computational studies suggest an origin for these relative rates.

To study the relative rates of the reactions of nucleophiles with allyl, benzyl, substituted allyl, substituted benzyl, and alkyl ligands in a systematic fashion, we prepared a series of cationic palladium complexes containing the same ancillary dative ligand, BINAP (Figure 1). These complexes were prepared by the methods in eqs 1−4. Allylpalladium complexes **1**[8] and **2**[4] were prepared by the reaction of 2 equiv of (*R*)-BINAP with allylpalladium chloride dimer or 1,1-dimethylallylpalladium chloride dimer, followed by abstraction of halide with AgOTf. η^3-Benzyl and η^3-naphthylmethyl complexes **3**[4] and **5** containing triflate counterions were prepared by the reaction of CpPd(η^3-allyl), with (*R*)-BINAP and a benzylic bromide to form the square planar complex ((*R*)-BINAP)Pd(CH_2-Ar)(Br), followed by abstraction of halide from the palladium bromide with AgOTf (eq 2). Phenethyl and naphthylethyl complexes **4** and **6** were prepared by first reducing ((*R*)-BINAP)$PdCl_2$ in the presence of the vinylarene to yield an η^2-vinylarene complex. This vinylarene complex was then converted to the η^3-arylethyl complex by protonation with anilinium triflate (eq 3). The cationic palladium methyl complex **7** was prepared by addition of (*R*)-BINAP to (COD)Pd(Me)(Cl), followed by treatment of the resulting (BINAP)-Pd(Me)(Cl) with AgOTf in a mixture of CH_2Cl_2 and pyridine.

New complexes **4**, **5**, **6**, and **7** were characterized by standard spectroscopic methods and elemental analysis. The η^3 hapticity of the allylic and benzylic ligands has been demonstrated by previous X-ray structural data on **1**[8] and on structures analogous to **2**[9], **3**,[4] and **6**.[7]

The reactions of aniline with complexes **1**−**3**, **5**, and **6** formed the corresponding amine in >95% yield, as determined by ^1H NMR spectroscopy. In contrast to the reactions of these five complexes with aniline to form addition products, the reaction of [((*R*)-BINAP)Pd(η^3-phenethyl)]OTf (**4**) with aniline predominantly formed free styrene and a mixture of Pd^0 complexes.[10]

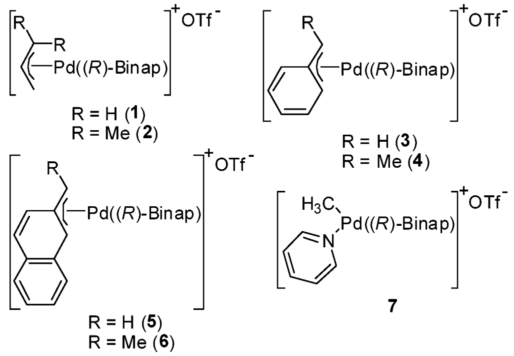
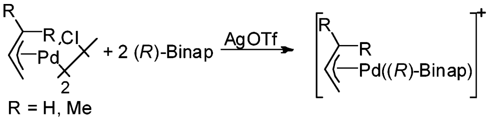
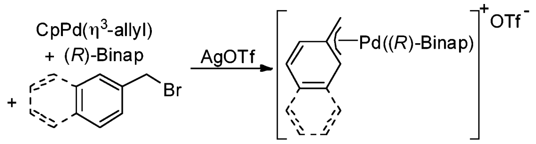


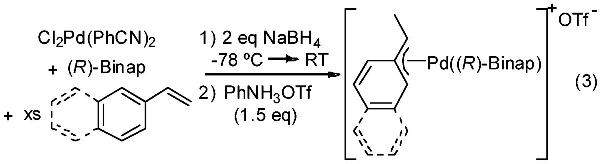
Figure 1. Complexes of η^3-π ligands investigated in this study.



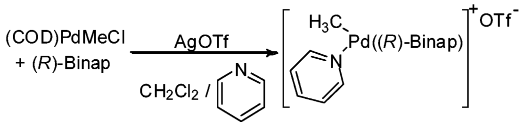
(1)



(2)



(3)



(4)

The rate of reaction of aniline with each of the complexes in Figure 1 (0.022 M) was measured with a 50-fold excess of aniline (1.08 M) in the presence of 10 equiv of diphenylacetylene (0.22 M) to trap the resulting palladium(0) product. The decay of the metal complexes in a 75:25 mixture of THF-d_8 and CD_2Cl_2 was monitored by ^1H NMR spectroscopy at 60 °C. The rate constants for these reactions are summarized in Table 1.[11]

The data in Table 1 show that the set of η^3-α-arylalkyl complexes all reacted faster than the two η^3-allyl complexes. The relative order of reaction was naphthylmethyl > naphthylethyl > benzyl >1,1-dimethylallyl > allyl. The half-lives of the reactions of dimethylallyl and allyl complexes **2** and **1** were 570 and 2200 min, respectively, whereas the half-lives of the reactions of the η^3-α-arylalkyl complexes **3**, **5**, and **6** ranged from only 11 to 185 min.

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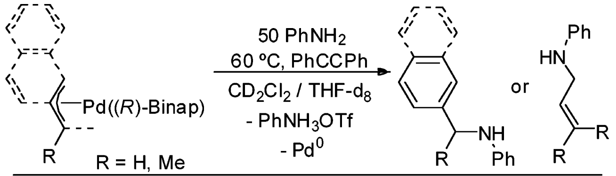
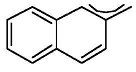
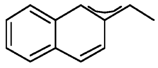
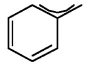
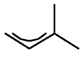
Table 1. Nucleophilic Addition of Aniline to **1**−**3**, **5**, and **6**[a]



entry	η^3 electrophile	$t_{1/2}$ (min)[b]	k_{obs} (s^{-1}) x 10^3 [b]
1		11	1.0
2		42 (15)	0.27 (0.79)
3		185 (159)	0.062 (0.072)
4		570 (7.1)	0.020 (1.63)
5		2200 (250)	0.0052 (0.046)

[a] Reaction conditions: 0.022 M Pd complex, 1.08 M aniline, 0.22 M PhCCPh, 9.0 mM 1,3,5-trimethylbenzene (internal standard) in 0.2 mL of CD$_2$Cl$_2$ and 0.6 mL of THF-d_8 at 60 °C. [b] Results in parentheses were obtained from reactions in 0.8 mL of DMSO-d_6.

In addition to revealing the fast rate of reaction of η^3-benzyl complexes, the data in Table 1 show the affect of steric and electronic components on the rate. The influence of steric interactions at the site of reaction is revealed by entries 1 and 2. The naphthylethyl complex **6** reacted about 4 times slower than the naphthylmethyl complex **5**. The influence of steric interactions ancillary to the site of attack is revealed by comparing entries 4 and 5 and was the opposite of the effect of steric interactions at the point of reaction. The two methyl groups on the dimethylallyl ligand of complex **2** increased the rate of reaction; complex **2** reacted roughly 4 times faster than the parent allyl complex **1**.

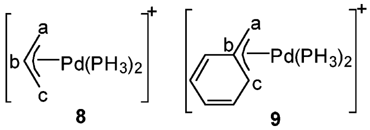
The effect of the extended aromatic system on the rate is revealed by comparing reactions of the naphthylmethyl and benzyl complexes. This extension of the aromatic system accelerated reaction of the η^3-α-arylethyl ligand by more than an order of magnitude. We suggest that this rate is faster because the η^2-arene complex formed initially from addition to the η^3-α-naphthylalkyl complex is more stable than that formed after addition to the η^3-α-phenylalkyl complexes.

To compare the rate of reaction of nucleophiles with these π-ligands with the rate of reaction with a σ-bound alkyl ligand, we conducted the reaction of aniline with [((*R*)-BINAP)Pd(CH$_3$)(pyridine)]OTf. No reaction occurred, even at high concentrations, elevated temperatures, and extended reaction times. This result is consistent with the scarcity of alkyl complexes that undergo nucleophilic attack or C−N bond-forming reductive elimination.[12]

To determine if these results were specific to reactions conducted in this solvent system, we conducted the reaction of aniline with **1**−**3**, **5**, and **6** in the more polar DMSO-d_6 (Table 1). Reactions of the α-arylalkyl complexes **3**, **5**, and **6** were faster in DMSO-d_8 than in THF-d_8/CD$_2$Cl$_2$ by a factor of 1.2−2.8; reactions of the allyl complex **1** were faster in DMSO by a factor of 8.8, while reactions of the dimethylallyl complex **2** were faster by a factor of about 80.[13] Thus, the relative order of reactivity of the benzyl and allyl complexes was retained, with the exception of complex **2**. Reaction of this complex did not occur with a clear first-order decay in DMSO, and future studies will be directed at understanding the factors that control the rate and regiochemistry of the reactions of this complex.

Computational studies were performed on model η^3-benzyl and η^3-allyl complexes to probe the origin of the difference in rate of reaction of these two classes of complexes. DFT calculations of the model complexes [(PH$_3$)$_2$Pd(η^3-allyl)]$^+$ (**8**) and [(PH$_3$)$_2$Pd(η^3-benzyl)]$^+$ (**9**) were conducted. The coordination geometries of the organic ligands were similar to those of experimental structures. To gain insight into the relative electrophilicities of these two compounds, APT charge calculations were performed. These calculations showed that the degree of positive charge at the site of nucleophilic attack (carbon a, Table 2) correlates with the observed rates of nucleophilic addition.[14]

Table 2. APT Charges for Model η^3-Benzyl and Allyl Complexes



8 **9**

	a	b	c
8	0.113	0.063	0.113
9	0.343	−0.193	0.122

In conclusion, studies of the effect of the electronic and steric properties of organometallic electrophiles on stoichiometric C(sp^3)−N bond formation revealed that addition to these η^3-benzyl complexes is faster than to the corresponding η^3-allyl complexes. This result implies that it should be possible to develop a body of transformations occurring by attack on η^3-benzyl and phenethyl ligands.[3,15]

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Supporting Information Available: Spectroscopic and analytical data of new compounds and experimental and computational procedures. This material is available free of charge via the Internet at http://pubs.acs.org.

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(10) Reaction of amine with an η^3-phenethyl complex is proposed to be the C−N bond-forming step of vinylarene hydroamination. The observation of this elimination process implies that the formation of this η^3-benzyl complex would be reversible during the catalytic process.
(11) Åkermark has argued that deprotonation of the ammonium salt, not C−N bond formation, is the irreversible step of the addition process. If so, our rate constants would reflect the combination of addition and deprotonation to form the final amine product. Vitagliano, A.; Åkermark, B. *J. Organomet. Chem.* **1988**, *349*, C22.
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