Olefin Hydroarylation

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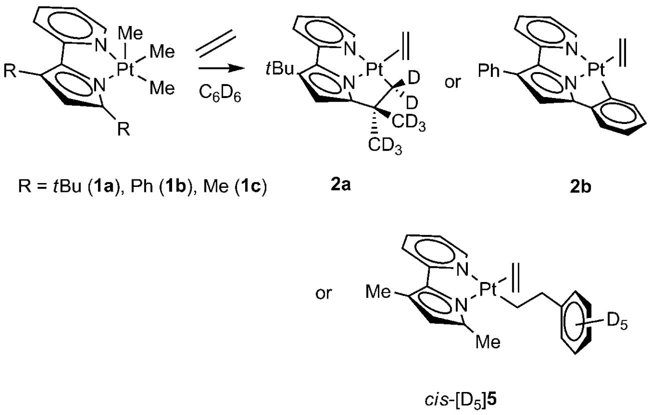
Intermolecular Hydroarylation of Unactivated Olefins Catalyzed by Homogeneous Platinum Complexes**

Avery T. Luedtke and Karen I. Goldberg*

The hydroarylation of olefins is a valuable C–C bond forming reaction used to produce alkyl arenes.[1] Olefin hydroarylation can be catalyzed by Lewis acids, but such reactions proceed through a Friedel–Crafts type mechanism involving an intermediary carbocation. Thus, these reactions give predominantly Markovnikov products, and *ortho*, *meta*, and *para* selectivity is determined by the substituents on the aromatic ring. In contrast, the use of transition-metal catalysts can afford different regioselectivities acting via a mechanism of arene C–H bond activation and olefin insertion.[1] While in the past transition-metal-catalyzed olefin hydroarylation reactions were primarily limited to activated arenes wherein a chelating functionality on the arene was available to assist and direct the C–H bond activation step,[1] recently Ir^{III} and Ru^{II} catalysts have demonstrated hydroarylation with unactivated arenes and olefins.[2,3] Mechanistic and computational studies on these Ir^{III} and Ru^{II} catalysts suggest that the hydroarylation does not proceed through a Friedel–Crafts type activation but through olefin insertion followed by oxidative hydrogen migration. In addition, selectivity for anti-Markovnikov over Markovnikov products (ca. 60:40) was observed. However, significantly higher selectivities and turnover numbers (TONs) are needed to make these processes economical, so a broadly tunable system that can be modified both sterically and electronically is likely needed.

One promising metal for olefin hydroarylation is platinum. There is considerable precedent for both arene C–H bond activation and olefin insertion at Pt^{II};[4,5] however, attempts at olefin hydroarylation with Pt^{II} have been disappointing.[6] Selectivities consistent with an electrophilic Friedel–Crafts type pathway were observed using a mixed Ag–Pt catalyst system.[7] With a related Pt^{II} catalyst, the hydroarylation of norbornene was reported, but other olefins were found to be unreactive.[8] Finally, tridentate chelation of a tris(pyrazolyl)borate ligand stabilized a potential Pt^{IV} intermediate preventing catalytic turnover.[5] Herein, we describe the rational development of an effective Pt^{II} system for intermolecular hydroarylation with unactivated arenes and olefins and present mechanistic evidence consistent with a pathway involving aryl–olefin insertion and C–H bond oxidative addition at Pt^{II}. While Markovnikov products are favored, anti-Markovnikov products are observed, and the mechanistic insight gained is promising for rational design of more selective and productive Pt^{II} catalysts for these reactions.

We recently reported that thermolysis of the five-coordinate Pt^{IV} complexes [(LX)PtMe$_3$] {LX = dtbpp [3,5-di-*tert*-butyl-2-(2-pyridyl)pyrrolide] (**1a**) or dppp [3,5-diphenyl-2-(2-pyridyl)pyrrolide] (**1b**)} at 85–100 °C in C_6D_6 in the presence of C_2H_4 (9–60 equivalents) led to the release of ethane and methane and formation of Pt^{II} complexes **2a** or **2b**, which contain a cyclometalated substituted pyrrolide group and C_2H_4 (Scheme 1).[9] This indicates that the (pyridyl)pyrrolide ligand on Pt^{II} effectively promoted two key reaction steps needed for hydroarylation: C–H bond activation and olefin coordination. The stability of the cyclometalated complexes, however, prevents further reaction. A complex containing a ligand that does not form a stable cyclometalation product may be expected to show different reactivity, and so [(dmpp)PtMe$_3$] [dmpp = 3,5-dimethyl-2-(2-pyridyl)pyrrolide (**1c**)] was prepared. Deprotonation of dmpp-H (**3**)[10] with KH in THF yielded green dmpp-K (**4**). Reaction of **4** with [{PtMe$_3$OTf}$_4$] (OTf = $SO_3CF_3^-$) in Et$_2$O produced a yellow solution of **1c**.[11] Although an X-ray crystal structure of **1c** reveals a non-centrosymmetric dimeric structure in the solid state with a long bond [2.518(8) Å] between the C4-pyrrolide carbon and a second Pt center (see Figure S16 in the Supporting Information), the ^1H NMR spectrum of **1c** in CD_2Cl_2 at room temperature is consistent with a fluxional five-coordinate complex.[12]



Scheme 1.

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[*] A. T. Luedtke, Prof. K. I. Goldberg
Department of Chemistry, Box 351700
University of Washington, Seattle, WA 98195-1700 (USA)
Fax: (+1) 206-685-8665
E-mail: goldberg@chem.washington.edu

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Remarkably, the change to methyl substituents on the (pyridyl)pyrrolide ligand allowed for the observation of Pt-catalyzed intermolecular hydroarylation of unactivated olefins. Similar to the thermolyses of **1a** and **1b**, upon thermolysis of **1c** at 100 °C for 5 h in C_6D_6 in the presence of C_2H_4 (70 equiv) ethane and methane (CH_4 and CH_3D) were released. However, rather than a cyclometalated Pt^{II} species, the Pt^{II} product $[(dmpp)Pt(CH_2CH_2C_6D_5)(C_2H_4)]$ (*cis*-$[D_5]$**5**) was observed in a 48% yield by ^1H NMR spectroscopy (Scheme 1). The configuration (*cis*) was assigned by NOESY[11] and refers arbitrarily to the position of the 2-phenethyl ligand with respect to the pyrrolide group. Notably, the product of hydroarylation, $C_6D_5CH_2CH_2D$ ($[D_6]$ethylbenzene), was also observed in the ^1H NMR spectrum, and the concentration of this organic product continued to increase upon further heating for an additional 12 h.

However, complex *cis*-$[D_5]$**5** decomposed significantly over this time to intractable products. The organic product, $C_6D_5CH_2CH_2D$, was identified by ^1H NMR spectroscopy and GC-MS. When C_6D_{12} was used as the solvent with C_2H_4 and C_6H_6 (0.21 M) added as reagents, no evidence of hydroarylation (or hydroalkylation) was observed in the ^1H NMR spectrum. Instead, decomposition of **1c** to Pt^0 was observed with evidence of numerous unidentified compounds in the ^1H NMR spectrum.

A related Pt^{II} catalyst precursor compound $[(dmpp)Pt(SMe_2)Ph]$ (*trans*-**6**) was prepared by the reaction of **3** with $[\{Me_2Pt(\mu\text{-}SMe_2)\}_2]$ in C_6H_6.[13] The relative configuration, phenyl *trans* to pyrrolide, was confirmed by NOESY.[11] Heating a C_6D_6 solution of *trans*-**6** at 100 °C caused partial isomerization to *cis*-**6** (greater than 2:1 *cis*/*trans* after 133 h).[11] Upon pressurization of a C_6D_6 solution of *trans*-**6** with C_2H_4 and subsequent heating at 59 °C for 14 h, conversion to *cis*-$[D_5]$**5** (59%) was observed in the ^1H NMR spectrum. Heating of either *cis*-$[D_5]$**5** or *trans*-**6** under C_2H_4 in C_6D_6 at 100 °C produced the hydroarylation product $C_6D_5CH_2CH_2D$. Similar attempts to synthesize $[(dmpp)Pt\{(C_3H_6)C_6H_5\}(C_3H_6)]$ by heating *trans*-**6** in C_6D_6 at 59 °C under an atmosphere of C_3H_6 were unsuccessful. However, *trans*-**6** can act as a precatalyst for the hydroarylation of C_3H_6 with C_6H_6 or $C_6H_5CH_3$ (Table 1).[14]

Table 1: Products and TONs for the hydroarylation of olefins.[a]

Arene	Olefin	Cat.	TON	*o*/*m*/*p*	*i*Pr/*n*Pr
C_6H_6	C_2H_4	**1c**	26		
	C_3H_6		8		86:14
	cyclohexene		8		
	norbornene		10		
$C_6H_5CH_3$	C_2H_4		4	7:93[b]	
	C_3H_6		2	10:63:27	85:15
$C_6H_5CF_3$	C_2H_4		2	6:62:32	
C_6H_6	C_2H_4	*trans*-**6**	36		
	C_3H_6		18		85:15
$C_6H_5CH_3$	C_2H_4		12	6:94	
	C_3H_6		3	9:66:25	84:16

[a] Reaction conditions: 100–110 °C, 1–3 mol% of **1c** or *trans*-**6**, 17–50 h.[11,17] [b] *meta* and *para* isomers could not be resolved and are listed together.

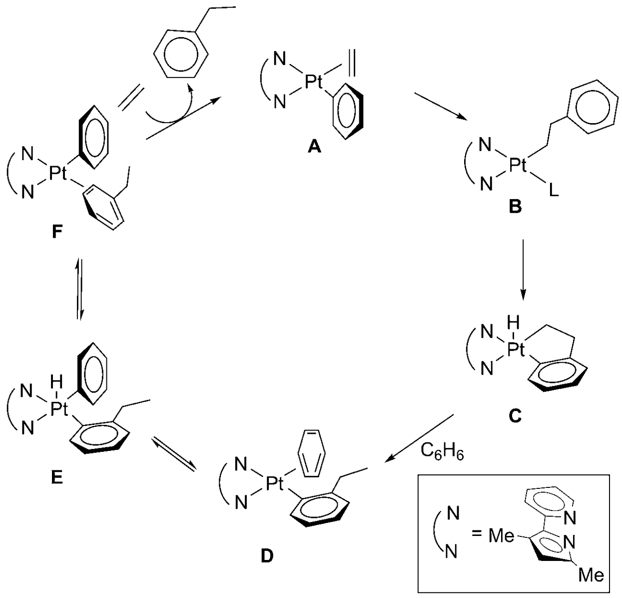
A variety of arene (C_6H_6, $C_6H_5CH_3$, $C_6H_5CF_3$) and olefin (C_2H_4, C_3H_6, cyclohexene, norbornene) combinations were examined with **1c** or *trans*-**6** as a precatalyst for hydroarylation. The product distributions were analyzed by GC-MS and GC-FID, and the results are summarized in Table 1 (a more complete listing can be found in Tables S1 and S2 in the Supporting Information).[11] Hydroarylation of C_2H_4 (390–410 mM initial concentration) in C_6H_6 to form ethylbenzene gave TONs of 26 (**1c**) or 36 (*trans*-**6**); the higher TON for *trans*-**6** compared to **1c** may be due to a more efficient conversion to the active catalyst. Notably, when multiple products are possible, hydroarylation product mixtures contain similar ratios using **1c** or *trans*-**6** as a precatalyst. With C_3H_6, both Markovnikov (*i*Pr-Ar) and anti-Markovnikov (*n*Pr-Ar) products are observed, with the former favored 5–6:1. The isomeric distribution *meta* > *para* > *ortho* was obtained for reactions with C_3H_6 in $C_6H_5CH_3$ (*o*/*m*/*p* 9:66:25) and C_2H_4 in $C_6H_5CF_3$ (*o*/*m*/*p* 6:62:32). Both the fact that some anti-Markovnikov product is observed and that a preference for *meta* and *para* over *ortho* functionalization is observed suggest that a C–H bond activation pathway is operative.

A small amount of styrenes (0.1–0.7 TON), presumably formed by β-hydride elimination and also some dialkylation products (0.5–1.6 TON) were observed.[11] Increasing the amount of C_2H_4 from 220 to 390 mM caused a 1.4-fold increase in TON in the hydroarylation of C_6H_6 using **1c** as the precatalyst. The relative amount of dialkylated products also increased from 4% to 9% of the total TON under these conditions.[11]

Reaction of C_2H_4 with a 1:1 solution of C_6D_6 and C_6H_6 using **1c** as the precatalyst gave $[D_0]$ethylbenzene through $[D_6]$ethylbenzene as observed by GC-MS, with the major product being $[D_3]$ethylbenzene (Supporting Information, Figure S15). This isotopomer distribution suggests rapid scrambling of H or D from the solvent (C_6H_6 or C_6D_6) into ethylbenzene.[11]

Stoichiometric reactions of *cis*-**5** or *cis*-$[D_5]$**5** in C_6D_6 with no C_2H_4 present produced $PhCH_2CH_3$ or $PhCH_2CH_2D$, respectively, as determined by ^1H NMR spectroscopy.[11] Thus, whether or not the C2 carbon of ethylbenzene bears one D or only H is dependent upon whether the phenyl group of the 2-phenethyl ligand of *cis*-**5** was deuterated or not.

The mechanism shown in Scheme 2 is consistent with the isotopic labeling results and the regioselectivity described above. A Pt^{II} phenyl ethylene complex, **A**,[15] formed in situ from **1c** or *trans*-**6**, undergoes migratory insertion of olefin into the Pt–Ph bond. Aryl C–H bond cyclometalation of the phenethyl group of **B** forms **C**. Insertion of an olefin into a Pt^{II}–Ph bond followed by orthometalation of the Ph ring has recently been observed upon thermolysis of $[Tp^{Me_2}PtPh(C_2H_4)]$ [Tp^{Me_2} = 3,5-dimethyl-tris(pyrazolyl)borate].[5] The observation of *cis*-**5** and the results of the stoichiometric reactions of *cis*-**5** and *cis*-$[D_5]$**5** are consistent with a similar reaction sequence in this system. However, here a five-coordinate cyclometalated hydrido Pt^{IV} species **C** would be formed, and alkyl C–H reductive elimination from five-coordinate Pt^{IV} structures is well precedented.[4] Coordination of the solvent to the Pt^{II} product of C–H reductive elimi-



Scheme 2. Proposed mechanism for the hydroarylation of C_2H_4 with C_6H_6. The ligand L in **B** may be an open site, C_2H_4 (complex **5**), or SMe_2.

nation would produce intermediate **D**, and a rapid equilibrium between arene complexes **D** and **F** would account for the H,D exchange observed in the hydroarylation of C_2H_4 using a 1:1 mixture of C_6H_6 and C_6D_6. Scrambling of H,D between Pt-bound Ph and arene groups has been previously reported.[16] Replacement of the bound arene of **F** with an olefin releases the product giving **A**. Displacement of the arene in **D** by the olefin would lead to the formation of dialkylated arene products, and β-hydride elimination from **B** would lead to styrene formation.

In summary, Pt-catalyzed intermolecular hydroarylation of unactivated olefins has been rationally developed. Studies of regioselectivity, relative reactivity of substrates, and deuterium labeling are consistent with a mechanism of olefin insertion into a Pt^{II}–aryl bond and aryl C–H oxidative addition at Pt^{II} center. Modification of both the sterics and the electronics of the (pyridyl)pyrrolide ligand to promote greater selectivity for anti-Markovnikov hydroarylation products and to increase the lifetime of the catalysts are currently under investigation.

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[11] See the Supporting Information.

[12] At low temperature (−53 °C), the ^1H NMR and NOESY spectra of **1c** in CD_2Cl_2 are consistent with the proposed dimeric structure.

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[14] Heating a C_6D_6 solution of $[\{PtMe_3OTf\}_4]$ or $[\{Me_2Pt(\mu\text{-}SMe_2)\}_2]$ at 100 °C under C_2H_4 does not produce $[D_6]$ethylbenzene.

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[17] TONs were determined by GC-FID using the relative peak areas versus an internal naphthalene standard. Relative response factors versus the naphthalene standard were determined from authentic samples that are commercially available: ethylbenzene, 2-phenylpropane, 1-phenylpropane, *p*-ethyltoluene, *o*-ethyltoluene, phenylcyclohexane, *m*-cymene, *p*-cymene, and *o*-cymene. The relative response factors of the other products were assumed to be unity.