Anti-Markovnikov Olefin Arylation Catalyzed by an Iridium Complex

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Significant efforts have been directed at homogeneous C−H bond activation of aromatic compounds by discrete transition metal complexes.[1] In view of the unusual product selectivity possible from reactions proceeding through the CH activation reaction, exploitation of catalysis through this reaction has attracted considerable attention. In the presence of an oxidant, Pd complexes catalyze oxidative vinylation of benzene with ethylene to produce styrene[2] or oxidative coupling of benzene to give biphenyl.[3] Murai et al. has reported alkylations of aromatic ketones by olefins. The reaction is catalyzed by Ru complexes to afford products that are not easily obtainable by conventional synthetic methods. In this system an acyl group is required to activate the ortho C−H bonds of the aromatic ring for alkylation to occur.[4] Other related CH activation reactions of aromatics that require the presence of activating functional groups are the alkylation of pyridines and aromatic nitriles.[5]

Herein we report the novel, anti-Markovnikov, arylation of olefins with benzene to produce straight-chain alkylbenzenes with higher selectivity than the branched alkylbenzene. The reaction, catalyzed by the binuclear Ir (III) complex, [Ir(μ-acac-O,O,C^3)-(acac-O,O)(acac-C^3)]$_2$, **1**,[6] is assumed to occur by the CH activation of the aromatic CH bonds. In contrast, conventional Friedel−Crafts alkylation of aromatic compounds with olefins, catalyzed by Lewis and Brönsted acid activation of the olefin, follow Markovnikov's rule, producing branched alkylbenzenes in nearly 100% selectivity.[7]

Table 1. Alkylation of Benzene with Various Olefins[a]

entry	catalyst	olefin	reaction time	TN[b]	TOF[b] ($\times 10^{-4}$ s^{-1})	selectivity[c] product	(%)
1	**1**	ethylene	3 h	455	421	ethylbenzene	*k*
2	**1**	ethylene	20 min	50	418	ethylbenzene	*l*
3	**1**	propylene[d]	20 min	13	110	*n*-propylbenzene	61
						cumene	39
4	**1**	i-butene[e]	2 h	2	3	*iso*-butylbenzene	82
						tert-butylbenzene	18
5	**1**	1-hexene[f]	20 min	8	69	1-phenylhexane	69
						2-phenylhexane	31
						3-phenylhexane	0
6	**1**	methyl acrylate[g]	20 min	5	39	3-PPAME[h]	68
						2-PPAME[i]	32
7	$AlCl_3$[j]	ethylene	20 min	26	218	ethylbenzene	*m*
8	$AlCl_3$[j]	propylene[d]	20 min	95	795	*n*-propylbenzene	0
						cumene	100
9	$AlCl_3$[j]	1-hexene[f]	20 min	67	554	1-phenylhexane	0
						2-phenylhexane	66
						3-phenylhexane	34

[a] Reaction temperatures are 180 °C for **1** and 50 °C for $AlCl_3$. [b] TN and TOF are based on Ir for **1**. [c] Selectivity in mono-alkylated aromatic compounds. [d] 0.78 Mpa of propylene, 1.96 Mpa N_2. [e] 0.20 Mpa of i-butene 1.96 Mpa N_2. [f] Benzene/1-hexene solution containing 8.8 M of benzene. 1.96 Mpa of N_2. [g] Benzene/methyl acrylate solution containing 10.1 M of benzene. 1.96 Mpa of N_2. [h] 3-Phenylpropionic acid methyl ester. [i] 2-Phenylpropionic acid methyl ester. [j] $AlCl_3$ was conducted into an autoclave under N_2. [k] [ethylbenzene (EB)] = 279 mM, [diethylbenzene (DEB)] = 9 mM. [l] [EB] = 48 mM, [DEB] = 2 mM. [m] [EB] = 426 mM, [DEB] = 20 mM.

Even when shape selective, acidic zeolites are employed for Friedel−Crafts alkylations, it is almost impossible to obtain straight-chain alkylbenzene.[8] Typically, to synthesize straight chain alkyl aromatics, a combination of Friedel−Crafts acylation and Clemenson reduction is employed. Using the reactions described herein, it is possible to obtain the straight chain product in one step using unactivated olefins and aromatics.

For example, when benzene and **1** were heated in the presence of ethylene at 180 °C for 3 h, ethylbenzene was obtained (TOF = 0.0421 s^{-1}, TN = 455; Table 1, entry 1).[9] Alkylation of benzene with propylene resulted in formation of *n*-propylbenzene and cumene in 61 and 39% selectivities, respectively (Table 1, entry 3). Showing the generality of the reaction and the preference for anti-Markovnikov additon, reaction with 1-hexene and isobutene (Table 1, entries 5 and 4) resulted in 1-phenylhexane (69% selectivity) and isobutylbenzene (82% selectivity), respectively. As a comparison, using $AlCl_3$ as a typical Friedel−Crafts catalyst, only Markovnikov addition products were observed (Table 1, entries 7, 8, and 9). Alkylation of toluene with ethylene gave only *m*- and *p*-ethyl methylbenzene in 63 and 37% selectivity: no ortho addition products were observed. Similarly ethylbenzene gave *m*- and *p*-diethylbenzene in a 7:3 ratio, respectively. This selectivity for meta and para substitution, presumably driven by sterics, has also been observed in other CH activation systems. For example, toluene is activated in the meta and para positions by OsH(Neopentyl)(PMe$_3$)$_4$ in statistical 2:1 ratio to produce

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(1) (a) Zhou, R.; Wang, C.; Hu, Y.; Flood, T. C. *Organometallics* **1997**, *16*, 434. (b) Selmeczy, A. D.; Jones, W. D.; Osman, R.; Perutz, R. N. *Organometallics* **1995**, *14*, 5677. (c) Meyer. T. Y.; Woerpel, K. A.; Novak, B. M.; Bergman, R. G. *J. Am. Chem. Soc.* **1994**, *116*, 10290. (d) Jones, W. D.; Hessell, E. T. J. *J. Am. Chem. Soc.* **1992**, *114*, 6087. (e) Boese, W. T.; Goldman, A. S. *Organometallics*, **1991**, *10*, 782−786. (f) Flood, T. C. In *Electron Deficient Boron Carbon Clusters*; Olah, G. A., Wade, K., William, R. E., Eds.; Wiley: New York, 1991, pp 309−349. (g) Kozhevnikov, I. V.; Kim, V. I.; Talzi, E. P.; Sidelnikov, V. N. *J. Chem. Soc., Chem. Commun.* **1985**, 1392. (h) Helden, R. V.; Verberg, G. *Rec. Trav. Chim.* **1965**, *84*, 1263. (i) Gretz, E.; Oliver, T. F.; Sen, A. *J. Am. Chem. Soc.* **1987**, *109*, 8109. (j) Hong, P.; Yamazaki, H. *J. Mol. Catal.* **1984**, *26*, 297. (k) Crabtree, R. H. *Chem. Rev.* **1985**, *85*, 245.

(2) (a) Fujiwara, Y.; Moritani, I.; Danno, S.; Asano, R.; Teranishi, S. *J. Am. Chem. Soc.* **1969**, *91*, 7166. (b) Taraban'ko, V. E.; Kozhevnikov, I. V.; Matveev, K. I. *Kinet. Katal.* **1978**, *19*, 1160. (c) Heck, R. F. In *Organic Reactions*; Adams, R. J., Eds.; Wiley: New York, 1982, pp 345−390.

(3) (a) Iataaki, H.; Yoshimoto, H. *J. Org. Chem.* **1973**, *38*, 76. (b) Rudenkov, A. I.; Mennenga, G. U.; Rachkovskaya, L. N.; Matveev, K. I.; Kozhevnikov, I. V. *Kinet. Katal.* **1977**, *18*, 915.

(4) (a) Murai, S.; Chatani, N.; Kakiuchi, F. *Pure Appl. Chem.* **1997**, *69*, 589. (b) Murai, S.; Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N. *Nature* **1993**, *366*, 529. (c) Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 62. (d) Trost, B. M.; Imi, K.; Davies, I. W. *J. Am. Chem. Soc.* **1995**, *117*, 5371.

(5) (a) Lim, YG.; Han, J. S.; Koo, B. T.; Kang, J. B. *Bull. Korean Chem. Soc.* **1999**, *20*, 1097. (b) Kakiuchi, F.; Sonoda, M.; Tsujimoto, T.; Chatani, N.; Murai, S. *Chem. Lett.* **1999**, 1083.

(6) Bennett, M. A.; Mitchell, T. R. B. *Inorg. Chem.* **1976**, *15*, 2936.

(7) Burgoyne, E. E. *A Short Course in Organic Chemistry*; McGraw-Hill Book Co.: Singapore, 1985; pp 137−139.

(8) Cao, Y.; Kessas, R.; Naccache, C.; Taarit, Y. B. *Appl. Catal. A* **1999**, *184*, 231.

(9) In a typical reaction protocol, a 10 mL stainless autoclave, equipped with a glass insert and a magnetic stir bar is charged with 3 mL of benzene saturated with water and 1.0 mg of **1**. The reactor is degassed with nitrogen, pressurized with 1.96 Mpa of ethylene and heated to 180 °C with stirring for 3 h. The liquid phase was sampled and analyzed by GC (FID) and GC−MS at the end of the reaction.

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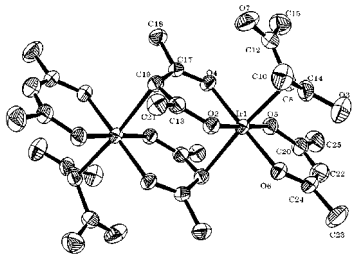

Figure 1. ORTEP drawing of complex **1**. Thermal ellipsoids are drawn at the 40% probability level.

Table 2. Alkylation of Benzene with Ethylene[a]

entry	catalyst	reaction media	TN[b]	TOF[b] ($\times 10^{-4}$ s^{-1})
10	**1**	distilled benzene	59	489
11	**1**	benzene saturated with H_2O	157	1304
12	**3**	benzene saturated with H_2O	0.6	4.7
13	**2**	benzene saturated with H_2O	0	0

[a] Conditions: 200 °C, 20 min. For reaction procedures, see Supporting Information.

Os−Ar species.[1f] Interestingly, naphthalene gave only 2-ethylnaphthalene.

Bennett et al. isolated **1** as a byproduct in the course of an attempt to improve the synthesis of Ir(acac)$_3$ (**2**). They determined the structure of **1** from NMR, IR, and elemental analysis, although no catalysis with **1** was reported.[6] We determined the crystal structure of **1** using a single-crystal X-ray diffraction analysis,[10] in which *p*-xylene was contained as a lattice solvent (Figure 1). As Bennett proposed, **1** is a dinuclear Ir(III) complex with three different types of coordinated acac ligands; a conventional bidentate, O-bonded acac, a γ-C-bonded acac, and a bridging acac ligand that connects the two Ir centers via an Ir−O,O to one metal center and an Ir−C bond from the central carbon of the acac ligand to the second Ir center.

Addition of a large excess of benzoyl chloride to **1** at ambient temperature gave [Ir(μ-acac-O,O,C^3)(acac-O,O)Cl]$_2$ (**3**) in 74% yield in which the γ-C-bonded acac group to the Ir center is replaced by chloride. The structure **3** is proposed on the basis of ^{1}H NMR, ^{13}C NMR, IR, FD-MS, and elemental analysis. In a related reaction, Pd(acac-O,O)(acac-C^3)py, which has a γ-C-bonded acac group, reacts with benzoyl chloride to give Pd(acac-O,O)(py)Cl.[11] As shown in Table 2, this complex is much less efficient than **1** for the alkylation reaction. As expected, given the known stability of **2**, it is inactive for the alkylation reaction.

In Friedel−Crafts alkylations, reactions with ethylene are typically slow compared to the reaction with substituted olefins because of the relative stabilities of the incipient carbonium ions. However, in the Ir-catalyzed alkylation reaction reported herein, ethylene reacts faster than substituted olefins. This coupled with the preference for anti-Markovnikov arylation of olefins is consistent with the proposal that the Ir-catalyzed alkylation does not proceed via an olefin activation, carbonium ion mechanism. Conproportionation between diethylbenzene and benzene, transethylation to produce ethyl benzene, that is readily catalyzed by Friedel−Crafts catalysts, is not catalyzed by **1**. Moreover the observation that the reaction is accelerated by addition of water, (Table 2, entry 11) a known inhibitor of Friedel−Crafts catalysts, is also consistent with the reaction not occurring via an olefin activation, carbonium type mechanism.

Table 3. H-D Exchange Reaction between C_6H_6 and CH_3COOD[a]

entry	catalyst	TN[b]	TOF[b] ($\times 10^{-2}$ s^{-1})
14	**1**	4570	762
15	**3**	120	20
16	**2**	0	0
17	Ir(acac)(CO)$_2$	12	2
18	$IrCl_3 \cdot 3H_2O$	1	0.2
19	[Ir(Cp*)Cl$_2$]$_2$	9	2
20	Ir(Cp*)(acac-O,O)(acac-C^3)	31	5

[a] Conditions: 160 °C, 10 min. For reaction procedures, see Supporting Information.

Although the mechanism of this Ir mediated alkylation has not yet been fully elucidated, we propose that the reaction occurs in three main steps: (A) aromatic CH bond activation by the Ir center to produce an Ir-phenyl intermediate species, (B) olefin insertion to produce an Ir-alkyl, and (C) product loss from the metal center. The CH activation reaction could occur by two plausible mechanisms: (i) electrophilic substitution of an aromatic CH bond by a coordinately unsaturated Ir(III) complex (possibly formed by cleavage of the added dimer) or (ii) oxidative addition of an unsaturated Ir(III) or Ir(I) (formed by in situ reduction) complex to an aromatic CH bond.[12]

To learn whether C−H activation of benzene was occurring, we examined the efficiency of various Ir complexes in catalyzing proton exchange (generally a good test for reversible CH activation) between C_6H_6 and CH_3COOD. Of complexes, **1**, **2**, and **3**, complex **1** shows the highest rates for deuterium incorporation (TOF = 7.6 s^{-1}, in C_6H_6/CH_3COOD (6 M of benzene) at 160 °C). As observed for the alkylation reaction (Table 2), complex **2** is inactive for proton exchange and the rate with **3** is significantly slower than that for **1**. Preliminary studies of other well-known Ir complexes such as Ir(acac)(CO)$_2$, $IrCl_3 \cdot 3H_2O$, [Ir(Cp*)Cl$_2$]$_2$ and Ir(Cp*)(acac-O,O)(acac-C^3)[13] show that these complexes are also inefficient for both the H/D exchange and alkylation reactions. This strong correlation between the efficiency of **1** for H/D exchange and alkylation strengthens our proposal that the reaction proceeds via CH activation (see Table 3).

In summary, we report a novel, anti-Markovnikov arylation of unactivated olefins with unactivated arenes catalyzed by the Iridium complex, **1**. The mechanism of the reaction has not yet been fully elucidated, but appears to involve phenyl CH activation by Ir to form an Ir-phenyl species.

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Supporting Information Available: Typical experimental procedures, NMR data, FD-MS data and elemental analysis data of **3**, and X-ray data for **1** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(10) Crystal data for **1**: $C_{30}H_{42}Ir_2$, T = 296 K, yellow, triclinic, P$\bar{1}$ (no. 2), a = 8.394(1) Å, b = 14.177(2) Å, c = 8.089(2) Å, α = 93.20(2)°, β = 96.77(2)°, γ = 98.74(1)°, V = 942.1(3) Å^3, Z = 1, R = 0.035, R_w = 0.037, GOF = 0.74.

(11) Baba, S.; Ogura, T.; Kawaguchi, S. *Bull. Chem. Soc. Jpn.* **1974**, *47*, 665.

(12) Oxidative addition for the CH activation is considered along with an electrophilic substitution mechanism in light of recent reports of reaction of a cationic Ir(III) complex with CH bonds that is proposed proceed via an Ir(V) species resulting from an oxidative addition mechanism (Burger. P.; Bergman, R. G. *J. Am. Chem. Soc.* **1993**, *115*, 10462; Arndtsen, B. A.; Bergman, R. G. *Science* **1995**, *270*, 1970; Steven, R. K.; Tilley, D.; Bergman, R. G. *J. Am. Chem. Soc.* **2000**, *122*, 1816). Results from theoretical calculations on this reported Ir(III) system (Strout, D. L.; Zari'c, S; Niu, S.; Hall, M. B. *J. Am. Chem. Soc.* **1996**, *118*, 6068) are consistent with the proposal of an oxidative addition mechanism.

(13) Rigby, W.; Lee, H.; Bailey, P. M.; McCleverty, J. A.; Maitlis, P. M. *J. Chem. Soc., Dalton* **1979**, 387.