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ARTICLE

Non-Directed, Carbonate-Mediated C-H Activation and Aerobic C-H Oxygenation with Cp*Ir Catalysts

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The effect of oxidatively stable L- and X-type additives on the activity of Cp*Ir catalyst precursors in the C-H activation of arenes has been studied. Turnover numbers for C-H activation of up to 65 can thus be achieved, as determined by H/D exchange in MeOH-D_4. In particular, carbonate additives are found to enhance the C-H activation reactivity of Cp*Ir(H_2O)$_3$(OTf)$_2$ (**1**) more significantly than L-type ligands investigated in this study. Based on these studies, Cp*Ir /carbonate systems are developed that catalyze the aerobic C_{sp3}-H oxygenation of alkyl arenes, employing air as oxidant.

Introduction

Cp*Ir complexes have been widely used as catalyst precursors in oxidative chemistry during the last 20 years. Some examples are water oxidation,[1] H_2 activation,[2] dehydrogenation,[3] transfer (de)hydrogenation,[3,4] and aerobic alcohol oxidation.[5-8] Furthermore, Cp*Ir complexes have been widely explored as catalysts for C-H activation and catalysts with a [Cp*Ir(PMe$_3$)] core are among the most active catalysts known in stoichiometric and catalytic scenarios.[9-12] However, translating this remarkable activity in C-H bond cleavage into reactivity for C-H bond functionalization has proven to be challenging, likely due to the oxidative sensitivity of the activating ligand PMe$_3$.

Thus, subsequent efforts have focused on synthesizing catalysts bearing similarly electron-donating, but oxidatively stable ligands. Several such examples have incorporated carbene and pyridine ligands and several such catalyst structures enable C-H activation as demonstrated by H/D exchange reactivity.[13-15] Interestingly, employing CO as ligand to replace PMe$_3$ results in a tendency to form bimetallic complexes, which are unreactive towards C-H bond cleavage.[16] Furthermore, several Cp*Ir complexes have been used as catalyst precursors for directed C-H functionalization, in which the directing group on the substrate likely acts as L-type ligand on the Ir center of the catalyst.[17-21] However, only two examples of non-directed (non-chelate assisted) C-H functionalizations with Cp*Ir catalysts have been reported.[22,23] In the first example, the use of the very strong oxidant ceric ammonium nitrate (CAN) whose presence has been shown to result in degradation of the Cp* ligand[24] makes it unlikely that the catalyst structure remains unchanged under these reaction conditions.[22,§] The second example oxidizes alkyl arenes selectively to the highest oxidized product, i.e. methyl arenes are transformed into benzoic acids and methylene groups in benzylic positions are transformed into the corresponding ketones.[23]

In summary, the search for Cp*Ir based C-H functionalization catalysts has mainly focused on varying L-type ligands. The new approach described in this manuscript evaluates the influence of oxidatively stable L- and X-type additives on the C-H activation performance of Cp*Ir catalyst precursors. The results of these investigations suggest that X-type additives – carbonates in particular – can render the Cp*Ir center highly activated towards C-H bond cleavage. Subsequently, combining this catalyst system with suitable carboxylic acids and air as oxidant establishes active catalysts for C_{sp3}-H oxygenations of alkyl arenes with selectivity for C-O bond formation in the benzylic position.

Results and discussion

H/D Exchange of Cp*Ir complexes

Our interest initially focused on establishing the effects of L-type and X-type additives, which had not been studied in detail in the literature, on C-H activation reactivity with Cp*Ir catalyst precursors. To this end, H/D exchange reactions were performed in MeOH-D_4 at 150 °C, generating data comparable to activity data already published.[13,14] In our hands, the catalyst precursor Cp*Ir(H_2O)$_3$(OTf)$_2$ (**1**) showed 11 ± 1 turnover numbers (TON) at a catalyst loading of 2 mol % (Table 1, entry 1);[‡] [Cp*IrCl$_2$]$_2$, a common catalyst precursor for oxidative chemistry[6,7,21] showed lower activity (3 ± 1 TON).

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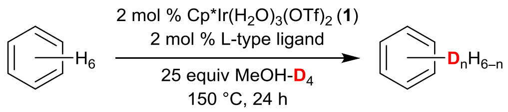
Interestingly, the simple addition of 4 mol % AgOTf, AgBF$_4$, or AgPF$_6$ to [Cp*IrCl$_2$]$_2$ did not result in high activity (1 to 5 TON). This suggests that – unlike in H/D exchange experiments with Pt and Pd catalysts[25,26] – the presence of AgCl is detrimental to C-H activation reactivity. Due to these results, **1** was used as catalyst precursor in all further studies.

Table 1. Results of H/D exchange with L- and X-type additives. Conditions: Cp*Ir(H$_2$O)$_3$(OTf)$_2$ (6.5 mg, 9.5 µmol, 2.0 mol %), additive (2.0 to 16 mol %), benzene (42 µL, 37 mg, 0.475 mmol, 1.00 equiv), MeOH-D$_4$ (0.48 mL, 0.43 g, 12 mmol, 25 equiv), 150 °C, 24 h.



Entry	Additive	TON	Entry	Additive	TON
1	-	11(1)	13	2 mol % Li$_2$CO$_3$	18(5)
2	**2**	21(10)	14	2 mol % Na$_2$CO$_3$	32(3)
3	**3**	17(4)	15	2 mol % Cs$_2$CO$_3$	33(8)
4	**4**	19(2)	16	2 mol % NaOAc	10(2)
5	**5**	27(12)	17	2 mol % NaO$_2$C^{t}Bu	10(4)
6	**6**	13(2)	18	2 mol % KF	10(2)
7	**7**	20(1)	19	4 mol % Li$_2$CO$_3$	53(1)
8	**8**	12(1)	20	4 mol % Na$_2$CO$_3$	46(6)
9	**9**	9(1)	21	4 mol % Cs$_2$CO$_3$	28(6)
10	**10**	14(1)	22	8 mol % Li$_2$CO$_3$	49(9)
11	**11**	18(1)	23	16 mol % Li$_2$CO$_3$	65(1)
12	**12**	<7(3)	24	2 mol % Na$_2$SO$_4$	23(4)

L-type Additives. Next, we evaluated the influence of different L-type ligands on the H/D exchange activity of **1**. We reasoned, that air-stable, electron-rich ligands such as phosphines (**2**, **3**, and **6**; Figure 1) or phosphine oxides (**4**, **5**) might mimic the influence of PMe$_3$ on the Ir center and promote C-H activation, while providing an oxidatively stable catalyst structure, which could then be further employed in oxidative C-H functionalization.

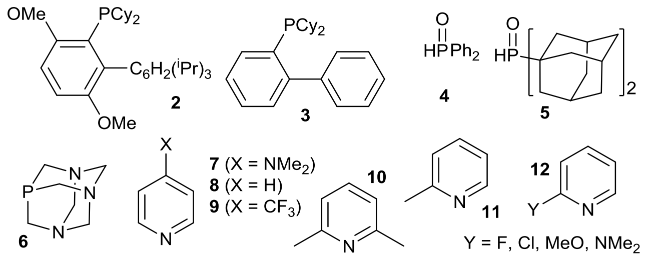


FIgure 1. L-type used in H/D exchange studies.

Indeed, all tested phosphines and phosphine oxides (entries 2-6, Table 1) provided higher reactivity (TONs up to 27) than the catalyst precursor **1** by itself (11 TON; entry 1). Interestingly, electron-rich pyridines (**7**, **10**, **11**) also provided higher TONs up to 20, while electron-poor pyridines (e.g. **9**) did not improve C-H activation activity as compared to the reaction in the absence of ligands. Overall, even though the activities obtained in these studies are not rivalling the reactivities obtained with analogous Cp*Ir(PMe$_3$) complexes,[10] they suggest that the identity of the L-type ligand is indeed important for promoting C-H activation in these catalyst structures.

X-type Additives. In a next step, we evaluated how X-type additives would affect the C-H activation reactivity of Cp*Ir(H$_2$O)$_3$(OTf)$_2$ (**1**), as prior work with complexes of the formular Cp*Ir(carbene)X$_2$ (X = SO$_4$, NO$_3$, O$_2$CCF$_3$, Cl, OTf) has shown such effects to be associated with the identity of the ligands X.[13] Interestingly, the presence of carbonate salts such as Na$_2$CO$_3$ or Cs$_2$CO$_3$ (Table 1, entries 14 and 15) resulted in significantly higher catalytic activity (32 and 33 TONs, respectively) than observed with any of the L-type ligands evaluated previously. Higher loadings of Li$_2$CO$_3$, Na$_2$CO$_3$, or Cs$_2$CO$_3$ enhanced this effect even further (entries 19 to 23), leading to up to 65 TON in H/D exchange. These TONs are comparable to TONs achieved previously with Cp*Ir(carbene) complexes in MeOH-D$_4$, which are the only known Cp*Ir complexes with oxidatively stable ligands that also show high reactivity in for non-directed C-H activation.[13,14,15] In contrast to the significant reactivity enhancement by carbonates, other X-type additives such as NaOAc, NaO$_2$C^{t}Bu, or KF (entries 16 to 18; 10 TON each) did not show analogous activating effects, while Na$_2$SO$_4$ (entry 24) promoted the H/D exchange activity similar to the carbonate additives (23 TON). These data suggest that carbonate additives are unique with regard to their ability to promote non-directed C-H activation at the Cp*Ir core; to the best of our knowledge, our observations are the first documentation of this effect. Involvement of carbonate ligands in C-H activation has previously been proposed for Pd catalysts;[27,28] these examples invoke the ability of carbonate ligands to act as internal bases, enabling C-H activation through a concerted metalation-deprotonation (CMD) pathway.[29,30]

C-H Oxygenation of Alkyl Arenes

Since carbonate additives showed reactivity enhancing effects on the C-H activation of benzene in MeOH-D$_4$, we reasoned that this reactivity might be transferable to establish oxidative C-H functionalizations of arenes. We focused on aerobic reactivity in the presence of air, as oxygen has previously been used in oxidations catalyzed by Cp*Ir complexes;[6,7] moreover, such conditions do not seem to suffer from the decomposition of Cp*Ir complexes observed with stronger, homogeneous oxidants.[24] We further reasoned that the used of *p*-xylene as substrate would provide valuable insight into the possibility of selective oxidation of C$_{sp2}$-H or C$_{sp3}$-H bonds.[31] Our initial experiments (Scheme 1, eq. 1) quantified the extent of background oxidation, which is expected at the benzylic position in the presence of O$_2$ at high temperatures.[32] Under

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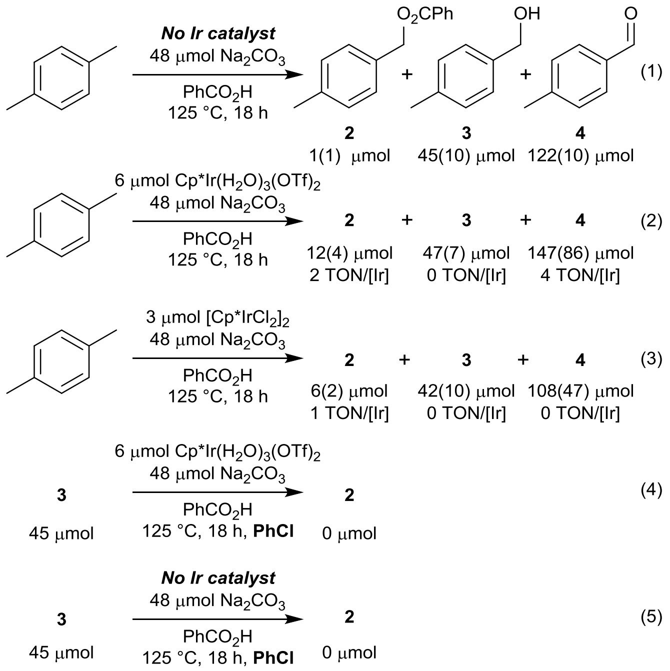
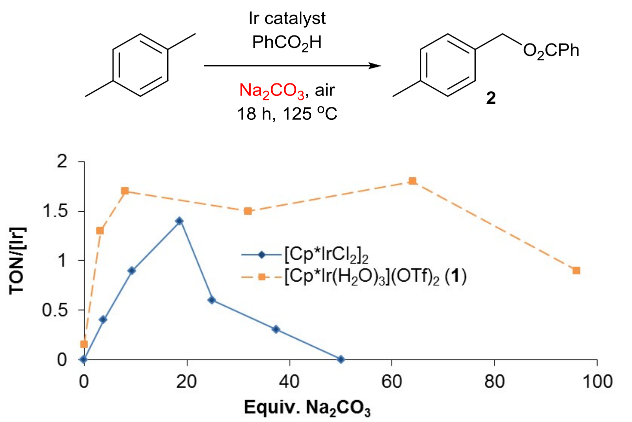
the used conditions, this reaction provided a mixture of products, with the benzylic ester **2** as the minor product and benzylic alcohol **3** and aldehyde **4** as major products. Excitingly adding either catalyst **1** or [Cp*IrCl$_2$]$_2$ to the reaction mixture resulted in a significant higher yield of ester **2** (Scheme 1, eq.s 2/3), while formation of **3** and **4** remained almost unaffected. Ester **2** could generally be formed through two plausible, Ir catalyzed pathways: (i) By esterification reaction between alcohol **3** and PhCO$_2$H or (ii) by C-H activation of *p*-xylene, followed by reductive elimination forming a new C-O bond. In order to distinguish between these two pathways, we reacted **3** (45 µmol; the amount typically formed in the non-catalyzed background reaction) with PhCO$_2$H in the presence and absence of Ir catalyst; these reactions were performed in PhCl as solvent in order to avoid formation of **3** or **2** from *p*-xylene, which would complicate the analysis of the resulting products. Interestingly, neither reaction in PhCl formed any ester product **2** (Scheme 1, eq.s 4/5), suggesting that formation of **2** as shown in eq.s 2/3 is unlikely to proceed through simple esterification. This allows us to determine TONs for these reactions, resulting in 1 TON/[Ir] for [Cp*IrCl$_2$]$_2$ as catalyst and 2 TON/[Ir] for **1**.



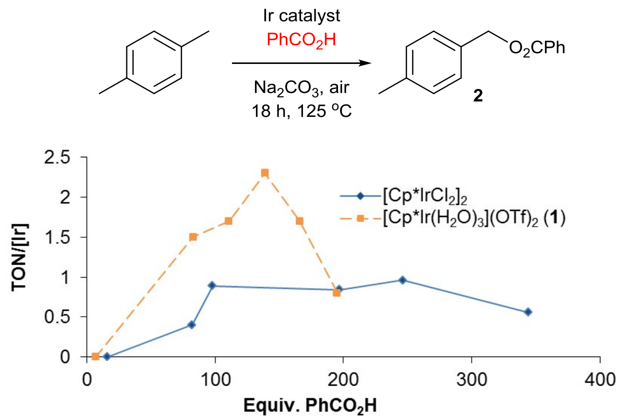
Scheme 1. Aerobic C-H Oxygenation of C$_{sp3}$-H Bonds by Cp*Ir/Carbonate: Initial Reactivity of Catalyst System and Background Reactions. Conditions: Ir catalyst (6 µmol [Ir], 1 equiv.), Na$_2$CO$_3$ (0 or 8 equiv.), *p*-xylene (1.5 mL, 2033 equiv.), benzoic acid (0 or 83 equiv.), 125 °C, 18 h. All values for TON/[Ir] are corrected for background reactivity. Conditions for esterification background: Cp*Ir(H$_2$O)$_3$(OTf)$_2$ (0 or 6 µmol [Ir]), Na$_2$CO$_3$ (47 µmol, 8 equiv.), benzoic acid (0.49 mmol, 82 equiv.), 125 °C, 18 h.

Optimizations of C-H Oxygenation. Having established that formation of **2** is dependent on the Cp*Ir catalysts employed, we investigated the effects of the different components of the reaction system on the catalytic activity (Schemes 2 to 4 and SI, Tables 7 to 13). Initial studies (Scheme 2) show a distinct dependence on the amount of added Na$_2$CO$_3$ at low loadings (<10 equiv.) for both catalysts (**1** and [Cp*IrCl$_2$]$_2$), suggesting that the carbonate additive plays a role in activating the catalytic reaction. A similar trend can be observed for PhCO$_2$H at low loadings (Scheme 3; <150 equiv.), while a larger excess of either Na$_2$CO$_3$ or PhCO$_2$H leads to a decrease in turnover. Different amounts of *p*-xylene, which is used both as substrate and as solvent in these reactions, do not show a clear influence on the TONs (see SI, Table 10).



Scheme 2. Effect of Na$_2$CO$_3$ Loading on TON. All values for TON/[Ir] are corrected for background reactivity. Equiv. Na$_2$CO$_3$ are based on 6 µmol [Ir] = 1 equiv. Conditions: Ir catalyst (6 µmol [Ir]), Na$_2$CO$_3$ (0 to 100 mg, 0 to 0.94 mmol, 0 to 160 equiv.), *p*-xylene (1.5 mL, 1.3 g, 12.2 mmol, 2033 equiv.), benzoic acid (60 mg, 0.49 mmol, 83 equiv.), 125 °C, 18 h.

In contrast, experiments evaluating the dependence of the catalytic activity (as characterized by TON) on the catalyst concentration show a clear dependence on the catalyst loading (Scheme 4) with higher TONs observed at lower catalyst loadings. This suggests that the catalytic activity observed here might suffer from catalyst decomposition to a bimetallic, catalytically inactive species as observed in the aerobic oxidation of alcohols.[6] Based on these observations, low catalyst loadings (1.5 µmol **1**) were used in the following experiments in order to favor high TONs.



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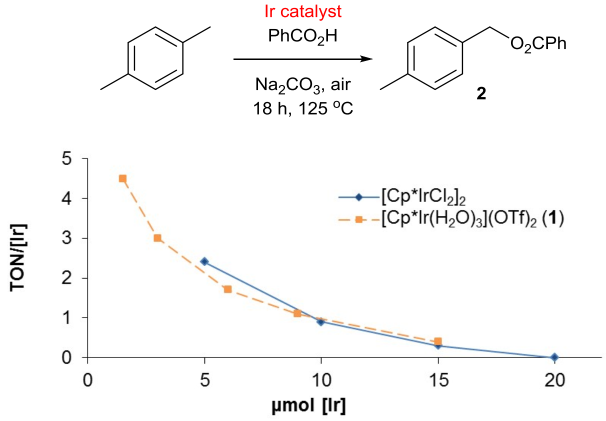
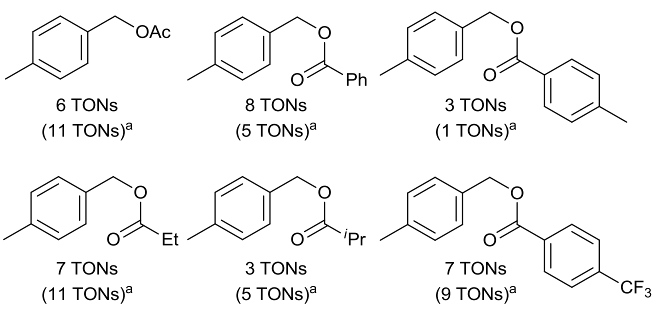
Scheme 3. Effect of Benzoic Acid Loading on TON. All values for TON/[Ir] are corrected for background reactivity. Equiv. $PhCO_2H$ are based on 6 µmol [Ir] = 1 equiv. Conditions: Ir catalyst (6 µmol [Ir]), Na_2CO_3 (5.0 mg, 0.047 mmol, 8.0 equiv.), *p*-xylene (1.5 mL, 1.3 g, 12 mmol, 2033 equiv.), benzoic acid (5 to 210 mg, 0.041 to 1.8 mmol, 7 to 344 equiv.), 125 °C, 18 h.

C-H Oxygenation: Carboxylic Acid Scope. Next, the generality of the catalytic system was explored, employing **1** as the superior catalyst in combination with a variety of carboxylic acids (Scheme 5). Depending on the carboxylic acid loading, TONs up to 11 were observed in these reactions; in particular, the carboxylic acids AcOH and $EtCO_2H$ resulted in high TONs. The more sterically bulky acid $^iPrCO_2H$ formed lower yields of the corresponding ester. Within the series of aromatic carboxylic acids tested, the electron-withdrawing substituent CF_3 favored ester formation, while the electron-donating substituent CH_3 resulted in lower yields and only 3 TON.



Scheme 4. Effect of Catalyst Loading on TON. All values for TON/[Ir] are corrected for background reactivity. Conditions: Ir catalyst (1.5 µmol to 15 µmol [Ir]), Na_2CO_3 (5 mg, 0.047 mmol), *p*-xylene (1.5 mL, 1.3 g, 12.2 mmol), benzoic acid (1.5 mL, 1.3 g, 12.2 mmol), 125 °C, 18 h.

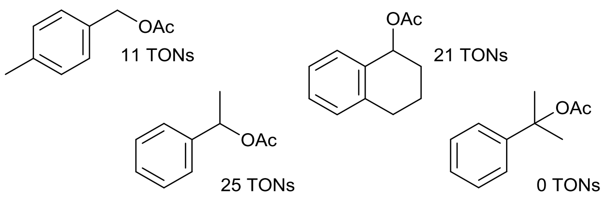


Scheme 5. Carboxylic Acid Scope. All values for TON are corrected for background reactivity (see SI, Table 15). Standard Conditions: **1** (1.0 mg, 1.5 µmol [Ir]), Na_2CO_3 (5.0 mg, 47 µmol, 31 equiv.), *p*-xylene (1.5 mL, 1.3 g, 12.2 mmol, 8133 equiv.), carboxylic acid (0.819 mmol, 546 equiv.), 125 °C, 18 h. [a]High Loading of Carboxylic Acid Conditions: as above, but 2.62 mmol carboxylic acid (1747 equiv.).

C-H Oxygenation: Alkyl Arene Scope. As AcOH provided high TONs in the previous study, AcOH was further employed in a short substrate scope study to gain insight into which types of C-H bonds can be oxygenated under the developed conditions (Scheme 6). Interestingly, both alkyl arenes with secondary benzylic C-H bonds provided higher TONs. In contrast, the tertiary benzylic C-H bond in cumene as substrate did not result in Ir catalyzed turnover, but produced a significant amount of oxygenated product in a non-catalyzed background reaction (151(8) µmol; see SI, Table 17).

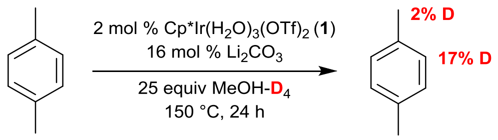
Preliminary Mechanistic Study: H/D Exchange with p-Xylene

Despite the many possible questions about the catalytic system, we considered the selectivity for the functionalization of benzylic C_{sp3}-H bonds to be particularly intriguing, as previous catalytic H/D exchange studies with $Cp^*Ir(PMe_3)Cl_2$ show selectivity for aromatic C_{sp2}-H and non-benzylic C_{sp3}-H bonds in alkyl arenes.[10] Furthermore, stoichiometric C-H activation with $Cp^*Ir(PMe_3)(CH_3)(OTf)$ also shows a preference for the cleavage of aromatic C_{sp2}-H bonds in alkyl arenes such as *o*-xylene and tetrahydronapththalene.[33]



Scheme 6. Aerobic Oxidation Products with Various Alkyl Arenes. All values for TON are corrected for background reactivity (see SI, Table 17). Conditions: **1** (1.5 µmol), Na_2CO_3 (47.2 µmol, 31 equiv.), alkyl arene (12.2 mmol, 8133 equiv.), AcOH (2.62 mmol, 1747 equiv.), 125 °C, 18 h.

In order to better understand if benzylic C_{sp3}-H activation can indeed occur under the developed reaction conditions, we performed H/D exchange of *p*-xylene in MeOH-D_4 in the presence of Li_2CO_3, in analogy to the best H/D exchange conditions established above for benzene as substrate. In agreement with the previously documents H/D exchange preference of $Cp^*Ir(PMe_3)Cl_2$,[10] a clear preference for aromatic C_{sp2}-H activation was observed (17% D incorporation; Scheme 7).



Scheme 7. H/D Exchange of p-Xylene. Conditions: **1** (9.5 µmol, 2.0 mol %), Li_2CO_3 (76 µmol, 16 mol %), MeOH-D_4 (0.48 mL, 0.43 g, 12 mmol, 25 equiv.), *p*-xylene (59 µL, 51 mg, 0.48 mmol, 1.0 equiv.), 150 °C, 24 h.

This suggests the possibility that initial C-H activation of *p*-xylene proceeds through C_{sp2}-H activation and that C_{sp3}-H activation is less favourable, but accessible under the reaction conditions. In this scenario, formation of the benzylic ester product could occur selectively, if the organometallic Ir-aryl

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and Ir-benzyl intermediates are in equilibrium; in this case, Curtin-Hammett control can be expected to favour the formation of benzyl ester, if it proceeds through a lower energy transition state than aryl ester formation. Further support for this mechanistic scenario comes from the observation that small amounts of aryl ester product are formed (TON <0.3) under the C-H oxygenation conditions developed above, indicating that principally both isomeric ester products can be accessed. However, in the absence of further mechanistic studies it is possible that the C-H activation and functionalization mechanism both act in unison, but are unrelated to each other.

Conclusions

In conclusion, this manuscript describes the discovery that carbonate additives can significantly influence the C-H activation reactivity of Cp*Ir-based catalyst precursors, as studied in detail by H/D exchange in MeOH-D_4. Remarkably, the resulting catalyst systems enable the aerobic C_{sp3}-H functionalization of alkyl arenes in benzylic position without the need for a catalyst directing group, forming ester products with up to 25 TONs. H/D exchange with *p*-xylene as substrate suggests that C_{sp2}-H activation is more favourable with the catalytic system than C_{sp3}-H activation, but further mechanistic studies need to be performed in order to better understand the effects of carbonates as well as the observed selectivity for benzylic C-H oxygenation.

Experimental

General Procedure for Benzylic Aerobic C-H Oxygenation. Cp*Ir catalyst ($[Cp^*IrCl_2]_2$ or $Cp^*Ir(H_2O)_3(OTf)_2$; 1.5 to 15 µmol [Ir]), carbonate additive (0 to 0.94 mmol, 0 to 160 equiv.), *p*-xylene (0.1 to 5.0 mL), and carboxylic acid (0.041 to 1.75 mmol, 7.0 to 344 equiv.) were mixed in a 20 mL scintillation vial. The vial was tightly sealed with a Teflon®-lined vial cap and heated to 125 °C for 18 h on a preheated vial plate. After the reaction time was complete, the mixture was allowed to cool to room temperature and PhBr (10 µL, 95 µmol) was added as GC standard. The mixture was extracted with H_2O (5 mL), the organic phase was filtered through celite, and the resulting filtrate was analyzed by GC-FID and/or GC-MS. Yields were determined by quantitative GC-FID analysis.

Acknowledgements

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Notes and references

‡ The obtained TON of 11(1) is in agreement with the previously determined TON of 16(2) for H/D exchange catalyzed by **1** (see ref. 14), considering that the spreadsheet used for calculating TONs based on incorporation of deuterium has a statistical error of ±5 TON.[25]

§ Even though the mild conditions applied here likely keep the Cp*Ir unit intact, it is possible that the benzylic C-H bonds in the Cp* ligand are attacked, which would lead to decomposition.[34]

1 a) U. Hintermair, S. W. Sheehan, A. R. Parent, D. H. Ess, D. T. Richens, P. H. Vaccaro, G. W. Brudvig and R. H. Crabtree, *J. Am. Chem. Soc.* 2013, **135**, 10837-10851; b) A. Savini, G. Bellachioma, G. Ciancaleoni, C. Zuccaccia, D. Zuccaccia and A. Macchioni, *Chem. Commun.* 2010, **46**, 9218-9219;c) J. D. Blakemore, N. D. Schley, G. W. Olack, C. D. Incarvito, G. W. Brudvig, R. H. Crabtree, *Chem. Sci.* 2011, **2**, 94-98; d) T. P. Brewster, J. D. Blakemore, N. D. Schley, C. D. Incarvito, N. Hazari, G. W. Brudvig, R. H. Crabtree, *Organometallics* 2011, **30**, 965-973; e) J. D. Blakemore, N. D. Schley, D. Balcells, J. F. Hull, G. W. Olack, C. D. Incarvito, O. Eisenstein, G. W. Brudvig, R. H. Crabtree, *J. Am. Chem. Soc.* 2010, **132**, 16017-16029; f) R. Lalrempuia, N. D. McDaniel, H. Müller-Bunz, S. Bernhard, M. Albrecht, *Angew. Chem. Int. Ed.* 2010, **49**, 9765-9768; g) J. F. Hull, D. Balcells, J. D. Blakemore, C. D. Incarvito, O. Eisenstein, G. W. Brudvig, R. H. Crabtree, *J. Am. Chem. Soc.* 2009, **131**, 8730-8731.
2 Z. M. Heiden, T. B. Rauchfuss, *J. Am. Chem. Soc.* 2009, **131**, 3593-3600.
3 a) R. Kawahara, K. Fujita, R. Yamaguchi, *Angew. Chem. Int. Ed.* 2012, **51**, 12790-12794; b) R. Kawahara, K.-i. Fujita, R. Yamaguchi, *J. Am. Chem. Soc.* 2012, **134**, 3643-3646; c) K. Fujita, T. Yoshida, Y. Imori, R. Yamaguchi, *Org. Lett.* 2011, **13**, 2278-2281; d) K. Fujita, N. Tanino, R. Yamaguchi, *Org. Lett.* 2007, **9**, 109-111; e) K.-i. Fujita, K. Yamamoto, R. Yamaguchi, *Org. Lett.* 2002, **4**, 2691-2694.
4 a) U. Hintermair, J. Campos, T. P. Brewster, L. M. Pratt, N. D. Schley and R. H. Crabtree, *ACS Catal.* 2013, **4**, 99-108.; b) T. P. Brewster, A. J. M. Miller, D. M. Heinekey and K. I. Goldberg, *J. Am. Chem. Soc.* 2013, **135**, 16022-16025. c) W. W. N. O, A. J. Lough, R. H. Morris, *Organometallics* 2012, **31**, 2152-2165; d) D. Gnanamgari, E. L. O. Sauer, N. D. Schley, C. Butler, C. D. Incarvito and R. H. Crabtree, *Organometallics*, 2008, **28**, 321-325; e) F. Hanasaka, K.-i. Fujita and R. Yamaguchi, *Organometallics*, 2005, **24**, 3422-3433; f) T. Suzuki, K. Morita, M. Tsuchida and K. Hiroi, *J. Org. Chem.* 2003, **68**, 1601-1602; g) S. Ogo, N. Makihara, Y. Kaneko, Y. Watanabe, *Organometallics* 2001, **20**, 4903-4910.
5 a) S. Arita, T. Koike, Y. Kayaki, T. Ikariya, *Angew. Chem. Int. Ed.* 2008, **47**, 2447-2449; b) A. Izumi, Y. Obora, S. Sakaguchi, Y. Ishii, *Tetrahedron Lett.* 2006, **47**, 9199-9201.
6 B. Jiang, Y. Feng, E. A. Ison, *J. Am. Chem. Soc.* 2008, **130**, 14462-14464.
7 A. Gunay, M. A. Mantell, K. D. Field, W. Wu, M. Chin and M. H. Emmert, *Cat. Sci. Techn.*, 2015, **5**, 1198-1205.
8 A. Gabrielsson, P. van Leeuwen and W. Kaim, *Chem. Commun.*, 2006, 4926-4927.
9 a) A. H. Janowicz and R. G. Bergman, *J. Am. Chem. Soc.*, 1982, **104**, 352-354. b) B. A. Arndtsen and R. G. Bergman, *Science*, 1995, **270**, 1970-1973.
10 S. R. Klei, J. T. Golden, T. D. Tilley and R. G. Bergman, *J. Am. Chem. Soc.*, 2002, **124**, 2092-2093.
11 B. A. Arndtsen, R. G. Bergman, T. A. Mobley and T. H. Peterson, *Acc. Chem. Res.*, 1995, **28**, 154-162.
12 S. R. Klei, K. L. Tan, J. T. Golden, C. M. Yung, R. K. Thalji, K. A. Ahrendt, J. A. Ellman, T. D. Tilley and R. G. Bergman, *ACS Symposium Series,* 2004, **885**, 46-55.

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13 Y. Feng, B. Jiang, P. A. Boyle and E. A. Ison, *Organometallics*, 2010, **29**, 2857-2867.
14 M. C. Lehman, J. B. Gary, P. D. Boyle, M. S. Sanford and E. A. Ison, *ACS Catal.*, 2013, **3**, 2304-2310.
15 R. Corberan, M. Sanau and E. Peris, *J. Am. Chem. Soc.*, 2006, **128**, 3974-3979.
16 J. M. Meredith, K. I. Goldberg, W. Kaminsky and D. M. Heinekey, *Organometallics*, 2009, **28**, 3546-3551.
17 K. Ueura, T. Satoh and M. Miura, *J. Org. Chem.*, 2007, **72**, 5362-5367.
18 L. Li, W. W. Brennessel and W. D. Jones, *J. Am. Chem. Soc.*, 2008, **130**, 12414-12419.
19 L. Li, Y. Jiao, W. W. Brennessel and W. D. Jones, *Organometallics*, 2010, **29**, 4593-4605.
20 T. M. Figg, S. Park, J. Park, S. Chang and D. G. Musaev, *Organometallics*, 2014, **33**, 4076-4085.
21 H. Kim, K. Shin and S. Chang, *J. Am. Chem. Soc.*, 2014, **136**, 5904-5907.
22 M. Zhou, D. Balcells, A. R. Parent, R. H. Crabtree and O. Eisenstein, *ACS Catal.*, 2011, **2**, 208-218.
23 Y. Yan, Y. Chen, M. Yan, X. Li and W. Zeng, *Catalysis Communications*, 2013, **35**, 64-67.
24 J. M. Thomsen, D. L. Huang, R. H. Crabtree and G. W. Brudvig, *Dalton Trans.,* 2015, **44**, 12452-12472.
25 A. J. Hickman, J. M. Villalobos and M. S. Sanford, *Organometallics*, 2009, **28**, 5316-5322.
26 M. H. Emmert, J. B. Gary, J. M. Villalobos and M. S. Sanford, *Angew. Chem. Int. Ed.*, 2010, **49**, 5884-5886.
27 I. A. Sanhueza, A. M. Wagner, M. S. Sanford and F. Schoenebeck, *Chem. Sci*, 2013, **4**, 2767-2775.
28 M. Chaumontet, R. Piccardi, N. Audic, J. Hitce, J. L. Peglion, E. Clot and O. Baudoin, *J. Am. Chem. Soc.*, 2008, **130**, 15157-15166.
29 Y. Boutadla, D. L. Davies, S. A. Macgregor and A. I. Poblador-Bahamonde, *Dalton Trans.*, 2009, 5820-5831.
30 M. H. Emmert, Introduction. In *C-H Bond Activation in Organic Synthesis*, J. J. Li, Ed. CRC Press: 2015; pp 1-20.
31 H. A. Zhong, J. A. Labinger and J. E. Bercaw, *J. Am. Chem. Soc.*, 2002, **124**, 1378-1399.
32 W.C. Fischer, R. Roehrscheid, Oxidation of alkyl-substituted aromatic compounds with air. In *Applied Homogeneous Catalysis with Organometallic Compounds*, B. Cornils, W. A. Herrmann, Eds. VCH: 1996; vol. 1, pp. 439-464.
33 D. M. Tellers, C. M. Yung, B. A. Arndtsen, D. R. Adamson and R. G. Bergman, *J. Am. Chem. Soc.*, 2002, **124**, 1400-1410.
34 J. Campos, U. Hintermair, T. P. Brewster, M. K. Takase and R. H. Crabtree, *ACS Catalysis*, 2014, **4**, 973-985. S. W. Sheehan, J. M. Thomsen, U. Hintermair, R. H. Crabtree, G. W. Brudvig and C. A. Schmuttenmaer, *Nature communications*, 2015, **6**, 6469.

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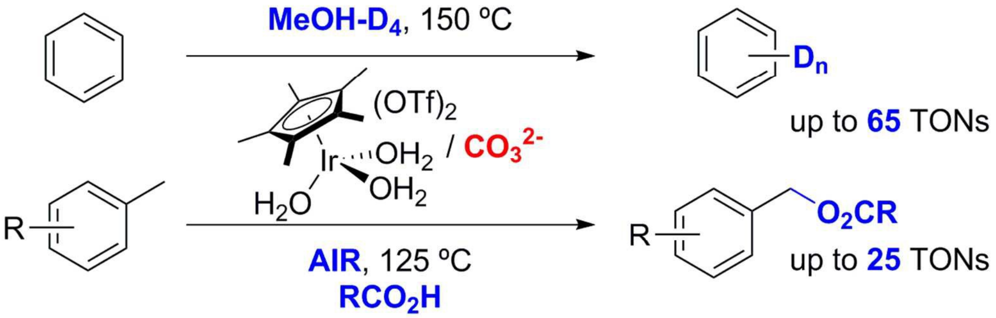

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