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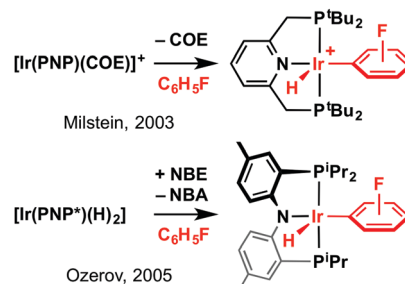
Iridium(i) carbonyl complex [Ir(2,6-(P^tBu₂CH₂)₂C₆H₃)(CO)] undergoes reversible C–H bond activation of benzene and a series of fluorobenzenes on UV irradiation. Exclusive *ortho*-selectivity is observed in reactions of fluorobenzene and 1,2-difluorobenzene.

Epitomised by applications in the catalytic dehydrogenation of alkanes, iridium complexes of phosphine-based pincer ligands are widely recognised for their capacity to activate C–H bonds.¹ With fluoroaryls representing valuable synthons in organic chemistry,^{2,3} we have targeted use of these iridium compounds for carrying out selective C–H bond activation reactions of partially fluorinated benzenes (C₆H_{6–n}F_n, *n* ≤ 3).³ The presence of fluorine substituents results in significantly stronger C–H bonds than benzene and, correspondingly, fluorobenzenes represent challenging substrates.^{3,4} Previous work by Milstein and Ozerov employing neutral (PNP) and anionic (PNP*) pincer ligands has highlighted the potential of iridium pincers, although under moderate temperature regimes (<100 °C) these systems showed poor regioselectivity in the activation of fluorobenzene (Scheme 1).⁵ As C–H bond activation is thermodynamically favoured *ortho* to the fluorine substituents,⁴ indiscriminate and irreversible oxidative addition reactions of transient 14 VE Ir(i) intermediates {Ir(PNP)}⁺/[Ir(PNP*)][–] are implicated.

We postulated that use of anionic pincer ligands bearing central aryl donors could promote selective activation of fluorobenzene substrates through increased reaction reversibility imparted by the high *trans*-influence aryl donor.^{6,7} With a view to testing this hypothesis we selected [Ir(PCP)(CO)] **1** (PCP = 2,6-(P^tBu₂CH₂)₂C₆H₃)⁸ as a well-defined precursor for the low coordinate and formally 14 VE Ir(i) fragment {Ir(PCP)}, through

photochemically promoted dissociation of the carbonyl ligand. In this way, subsequent products of C–H bond activation would be trapped on re-coordination of the carbonyl ligand (in a closed system). Initial experiments using benzene as the substrate supported this reasoning, with [Ir(PCP)(C₆D₅)D(CO)] **2-d₆**⁹ generated on irradiation of a 20 mM C₆D₆ solution of **1** at RT using a 100 W Hg arc lamp (quartz J. Young's NMR tube, Scheme 2). Following this reaction by periodic analysis using ³¹P NMR spectroscopy, however, indicated that conversion of **1** (δ_{31P} 82.0) to **2-d₆** (δ_{31P} 52.3) plateaued at 62% after *ca.* 2 h total irradiation. On the same timeframe, irradiation of independently synthesised **2** resulted in an equivalent reaction composition. In contrast, both **1** and **2** are thermally stable on extended heating at 80 °C in C₆D₆ solution (8 h) and no isotope exchange was observed for **2** (to **2-d₆**).¹⁰ Together these results indicate establishment of a photostationary mixture of **1** and **2-d₆**, mediated through light induced carbonyl dissociation from both species.¹¹

To gain deeper understanding of the photolysis experiments, a series of DFT and TD-DFT calculations were performed (see ESI† for full details). In line with expectation, the computed free energy for carbonyl dissociation to form {Ir(PCP)} is a significantly endergonic process (Δ*G*_{298K} = +194.4 kJ mol^{–1}). While the subsequent C–H bond activation of benzene is exothermic (Δ*H* = –15.3 kJ mol^{–1}),

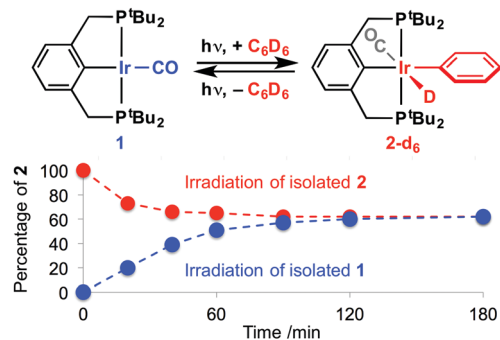


Scheme 1 C–H bond activation of fluorobenzene using Ir-pincers. PNP = 2,6-(P^tBu₂CH₂)₂C₅H₃N, PNP* = (4-Me-2-(P^tPr)₂C₆H₃)N[–], COE = cyclooctene, NBE = norbornene, NBA = norbornane.

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† Electronic supplementary information (ESI) available: Full experimental and computational details, NMR, IR and UV-vis spectra, TD-DFT analysis of **1** and **2**, and optimised geometries in xyz format. CCDC 1520522–1520525. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c6cc09807j





Scheme 2 UV-promoted interconversion between **1** and **2** ([Ir] = 20 mM, RT).

the Ir(III) product lies thermodynamically further uphill from **1** ($\Delta G_{298K} = +238.0 \text{ kJ mol}^{-1}$). Such energetics are characteristic of an unfavourable equilibrium reaction, although one that would be offset by the use of the substrate as the solvent.¹² Re-coordination of the carbonyl ligand counteracts the unfavourable thermodynamics ($\Delta G_{298K} = -95.0 \text{ kJ mol}^{-1}$), however, **2** is still calculated to be $+141.3 \text{ kJ mol}^{-1}$ higher in free energy than **1** + C_6H_6 . Together these results are consistent with the lack of any thermal reaction observed for either **1** or **2** in C_6D_6 and highlight the important promoting role of UV-irradiation in the formation of **2** (and reformation of **1**). In this context, analysis of **1** by TD-DFT identified a number of singlet-singlet electronic transitions between 195 and 235 nm (*i.e.* UV) that can be attributed to carbonyl dissociation. A representative example is shown in Fig. 1 (full details provided in ESI†). Similar excitations are also calculated for **2** between 190 and 260 nm, suggesting that it would be difficult to selectively enact the UV-promoted dissociation of carbonyl from either **1** or **2**.¹³

To further explore this C–H bond activation chemistry, 20 mM solutions of **1** in fluorobenzene, 1,2-difluorobenzene, and 1,3,5-trifluorobenzene were irradiated for a total of 8 h at RT (Scheme 3). Similar to that observed in benzene, analysis by ^1H and ^{31}P NMR spectroscopy indicated formation of photostationary mixtures composed of **1** and Ir(III) products of C–H bond activation **3**; as the minor and major components, respectively. Supporting our hypothesis, and contrasting with reactions of analogous PNP and PNP* systems (*vide supra*), C–H bond activation of fluorobenzene (**3a**) and 1,2-difluorobenzene (**3b**) proceeded with exclusive *ortho*-selectivity. Both possible rotamers of each isomer are formed, although in disparate proportions (Scheme 3).

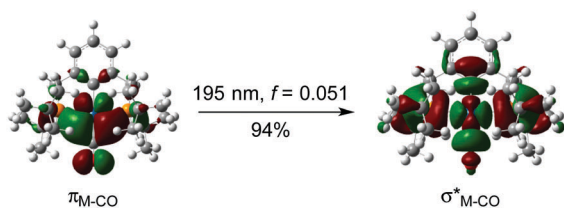
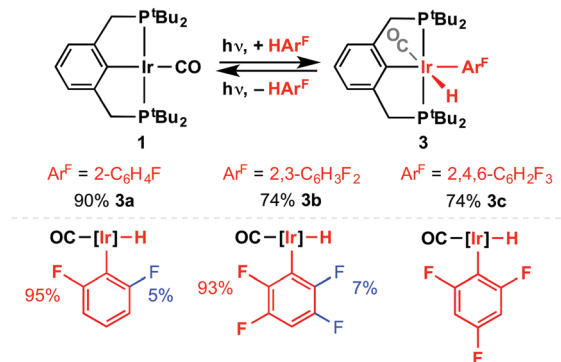


Fig. 1 Representative electronic excitation related to carbonyl dissociation from **1**; wavelength, oscillator strength (f) and % contribution of the represented natural transition orbitals (rendered with an orbital isosurface value of 0.02).



Scheme 3 UV-promoted C–H bond activation of fluorobenzenes (top; [Ir] = 20 mM, 8 h, RT). Major rotamers depicted in red, minor rotamers depicted in blue (bottom).

Consistent with these observations and manifestation of the “*ortho* fluorine effect”,⁴ the alternative regioisomers of **3a** ($>10 \text{ kJ mol}^{-1}$) and **3b** ($>18 \text{ kJ mol}^{-1}$), and their respective 5-coordinate precursors $[\text{Ir}(\text{PCP})(2\text{-FC}_6\text{H}_4)\text{H}]$ ($>24 \text{ kJ mol}^{-1}$) and $[\text{Ir}(\text{PCP})(2,3\text{-F}_2\text{C}_6\text{H}_3)\text{H}]$ ($>26 \text{ kJ mol}^{-1}$), are calculated to be significantly higher in free energy. As for the formation of **2** from **1**, computed reaction free energies suggest the formation of **3** occur outside of thermally accessible regimes and instead are presumably driven through nuanced differences in the photo-physical properties of **1** and **3**. Moreover, increasingly favourable overall reactions correlate with number of fluorine substituents: $\Delta G_{298K}/\text{kJ mol}^{-1} = +141.3$ (**2**), $+128.1$ (**3a**), $+121.0$ (**3b**), $+119.1$ (**3c**).

With the above in mind and to independently verify their structures, analytically pure samples of **3** were isolated through dehydrohalogenation of $[\text{Ir}(\text{PCP})\text{HCl}]^{14}$ using $\text{K}[\text{O}^t\text{Bu}]$ in the respective fluorobenzene at 75°C , followed by reaction with carbon monoxide (yield = 32–54%). The structures of these new compounds, and for comparison **2**,⁹ were fully verified in solution by ^1H , ^{13}C , ^{19}F and ^{31}P NMR, IR and UV-vis spectroscopy, and in the solid-state by X-ray crystallography (**3a**, **3b** – Fig. 2; **2**, **3c** – ESI†). Notable spectroscopic markers include low frequency hydride resonances at $\delta -9.07$ (**2**), $-8.86/-9.68$ (**3a**), $-8.88/-9.66$ (**3b**), -9.46 (**3c**) that show $^3J_{\text{PH}}$ coupling of *ca.* 17 Hz, and ^{31}P resonances at $\delta 51.1$ (**2**), $54.5/51.7$ (**3a**), $54.7/52.2$ (**3b**), 54.0 (**3c**) in C_6D_{12} solution (data for major rotamers underlined). The structures of major rotamers of **3a** and **3b**, bearing the fluorine atoms proximal to the carbonyl ligand, were definitively established in solution through NOESY experiments and corroborated in the solid-state (Fig. 2). Likewise, the hydride resonances of the minor rotamers show characteristic $^1J_{\text{FH}}$ coupling of *ca.* 10 Hz. The observed relative conformational preferences are also reproduced *in silico* (see ESI†). Complexes **3** are thermally stable on extended heating at 80°C in C_6D_6 solution: after 8 h, $<5\%$ **1** is formed and for **3a** and **3b** the ratio of rotamers was unchanged, as determined *in situ* by ^{31}P NMR spectroscopy.

In conclusion, we have demonstrated that selective C–H bond activation reactions of fluorobenzenes can be achieved under mild conditions using photolysis of $[\text{Ir}(2,6\text{-}(\text{P}^t\text{Bu}_2\text{CH}_2)_2\text{C}_6\text{H}_3)(\text{CO})]$ **1** as a means to generate the reactive



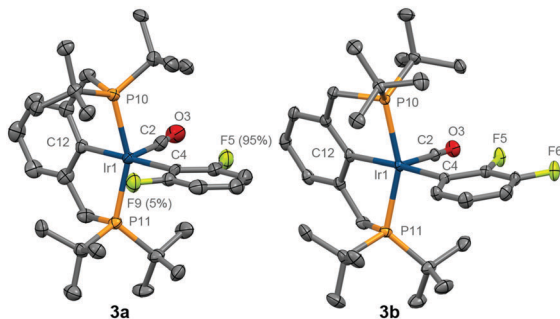


Fig. 2 Solid-state structures of **3a** (occupancy of disordered fluorine substituents in parenthesis) and **3b**. Thermal ellipsoids at 50% probability level; hydrogen atoms omitted for clarity. Selected bond lengths [Å] and angles [°]: **3a**, Ir1–C2, 1.931(6); Ir1–C4, 2.159(5); Ir1–C12, 2.115(5); Ir1–P10, 2.3394(15); Ir1–P11, 2.3474(15); C2–Ir1–C12, 83.8(2); C4–Ir1–C12, 178.2(2); P10–Ir1–P11, 155.84(5). **3b**, Ir1–C2, 1.928(2); Ir1–C4, 2.150(2); Ir1–C12, 2.111(2); Ir1–P10, 2.3511(6); Ir1–P11, 2.3397(6); C2–Ir1–C12, 89.07(9); C4–Ir1–C12, 173.63(8); P10–Ir1–P11, 157.41(2).

14 VE Ir(I) fragment $\{\text{Ir}(\text{2,6-(P}^t\text{Bu}_2\text{CH}_2)_2\text{C}_6\text{H}_3)\}$ in solution. This work not only showcases the ability of iridium pincer complexes to mediate challenging C–H bond activations, but more generally highlights a potentially useful catalyst design principle that we hope will stimulate the development of new organic transformations employing partially fluorinated benzenes as building blocks.

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Notes and references

- (a) K. Krogh-Jespersen, M. Czerw, K. Zhu, B. Singh, M. Kanzelberger, N. Darji, P. D. Achord, K. B. Renkema and A. S. Goldman, *J. Am. Chem. Soc.*, 2002, **124**, 10797–10809; (b) R. Ghosh, X. Zhang, P. Achord, T. J. Emge, K. Krogh-Jespersen and A. S. Goldman, *J. Am. Chem. Soc.*, 2007, **129**, 853–866; (c) W. H. Bernskoetter, P. S. White, K. I. Goldberg and M. Brookhart, *J. Am. Chem. Soc.*, 2009, **131**, 8603–8613; (d) J. Choi, A. H. R. MacArthur, M. Brookhart and A. S. Goldman, *Chem. Rev.*, 2011, **111**, 1761–1779; (e) J. Choi, D. Y. Wang, S. Kundu, Y. Choliy, T. J. Emge, K. Krogh-Jespersen and A. S. Goldman, *Science*, 2011, **332**, 1545–1548.
- For representative examples see: (a) M. Lafrance, C. N. Rowley, T. K. Woo and K. Fagnou, *J. Am. Chem. Soc.*, 2006, **128**, 8754–8756; (b) H.-Q. Do and O. Daugulis, *J. Am. Chem. Soc.*, 2008, **130**, 1128–1129; (c) Y. Nakao, N. Kashiwara, K. S. Kanyiva and T. Hiyama, *J. Am. Chem. Soc.*, 2008, **130**, 16170–16171; (d) X. C. Cambeiro, T. C. Boorman, P. Lu and I. Larrosa, *Angew. Chem., Int. Ed.*, 2012, **52**, 1781–1784; (e) P. Ricci, K. Krämer, X. C. Cambeiro and I. Larrosa, *J. Am. Chem. Soc.*, 2013, **135**, 13258–13261; (f) X. C. Cambeiro, N. Ahlsten and I. Larrosa, *J. Am. Chem. Soc.*, 2015, **137**, 15636–15639; (g) J. Takaya, S. Ito, H. Nomoto, N. Saito, N. Kirai and N. Iwasawa, *Chem. Commun.*, 2015, **51**, 17662–17665; (h) M. Simonetti, G. J. P. Perry, X. C. Cambeiro, F. Juliá-Hernández, J. N. Aronkianathar and I. Larrosa, *J. Am. Chem. Soc.*, 2016, **138**, 3596–3606.
- (a) E. Clot, O. Eisenstein, N. Jasim, S. A. Macgregor, J. E. McGrady and R. N. Perutz, *Acc. Chem. Res.*, 2011, **44**, 333–348; (b) S. D. Pike, M. R. Crimmin and A. B. Chaplin, *Chem. Commun.*, 2017, **53**, DOI: 10.1039/c6cc09575e.
- (a) M. E. Evans, C. L. Burke, S. Yaibuathes, E. Clot, O. Eisenstein and W. D. Jones, *J. Am. Chem. Soc.*, 2009, **131**, 13464–13473; (b) E. Clot, C. Mégret, O. Eisenstein and R. N. Perutz, *J. Am. Chem. Soc.*, 2009, **131**, 7817–7827; (c) E. Clot, M. Besora, F. Maseras, C. Mégret, O. Eisenstein, B. Oelckers and R. N. Perutz, *Chem. Commun.*, 2003, 490–491.
- (a) L. Fan, S. Parkin and O. V. Ozerov, *J. Am. Chem. Soc.*, 2005, **127**, 16772–16773; (b) E. Ben-Ari, M. Gandelman, H. Rozenberg, L. J. W. Shimon and D. Milstein, *J. Am. Chem. Soc.*, 2003, **125**, 4714–4715; (c) E. Ben-Ari, R. Cohen, M. Gandelman, L. J. W. Shimon, J. M. L. Martin and D. Milstein, *Organometallics*, 2006, **25**, 3190–3210.
- D. Y. Wang, Y. Choliy, M. C. Haibach, J. F. Hartwig, K. Krogh-Jespersen and A. S. Goldman, *J. Am. Chem. Soc.*, 2016, **138**, 149–163.
- During the preparation of this manuscript the C–H bond activation of fluorobenzene using related Ir-POCOP pincer complexes has been described: L. P. Press, A. J. Kosanovich, B. J. McCulloch and O. V. Ozerov, *J. Am. Chem. Soc.*, 2016, **138**, 9487–9497.
- (a) K. Krogh-Jespersen, M. Czerw, K. Zhu, B. Singh, M. Kanzelberger, N. Darji, P. D. Achord, K. B. Renkema and A. S. Goldman, *J. Am. Chem. Soc.*, 2002, **124**, 10797–10809; (b) D. Morales-Morales, R. Redón, Z. Wang, Do W. Lee, C. Yung, K. Magnuson and C. M. Jensen, *Can. J. Chem.*, 2001, **79**, 823–829.
- M. Kanzelberger, B. Singh, M. Czerw, K. Krogh-Jespersen and A. S. Goldman, *J. Am. Chem. Soc.*, 2000, **122**, 11017–11018.
- Acid catalysed oxidative addition of C(sp)³–H bonds to **1** have, however, been reported: J. D. Hackenberg, S. Kundu, T. J. Emge, K. Krogh-Jespersen and A. S. Goldman, *J. Am. Chem. Soc.*, 2014, **136**, 8891–8894.
- Consistent with this suggestion, photolysis of 20 mM solutions of **1** and **2** in C₆D₆ under 1 atm of CO at RT resulted in prolonged (>6 h) establishment of similar photostationary mixtures of **1**:**2-d₆** (1:1.4, corresponding to 58% **2-d₆**) to those obtained under an argon atmosphere (after ca. 2 h). For discussion of mechanistic pathways in related photochemical reactions of [Rh(PMe₃)₂(CO)Cl] see: G. P. Rosini, W. T. Boese and A. S. Goldman, *J. Am. Chem. Soc.*, 1994, **116**, 9498–9505.
- J. E. Wheatley, C. A. Ohlin and A. B. Chaplin, *Chem. Commun.*, 2014, **50**, 685–687.
- Notably using a long pass (glass) filter (<330 nm): no reaction was observed when a 20 mM solution of **1** was irradiated in C₆D₆ for 2 h at RT, while <5% formation of **1** was observed when a 20 mM solution of **2** was irradiated in C₆D₆ for 2 h at RT.
- C. J. Moulton and B. L. Shaw, *J. Chem. Soc., Dalton Trans.*, 1976, 1020.

