ChemComm

Cite this: *Chem. Commun.*, 2012, **48**, 443–445

www.rsc.org/chemcomm

COMMUNICATION

Electrophilic fluorination of cationic Pt-aryl complexes†

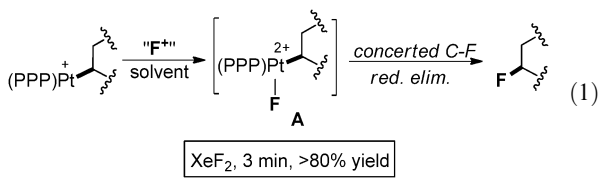
Shu-Bin Zhao,[a] Rui-Yao Wang,‡[b] Ha Nguyen,[a] Jennifer J. Becker[c] and Michel R. Gagné*[a]

Received 11th August 2011, Accepted 29th October 2011
DOI: 10.1039/c1cc15006e

The electrophilic fluorination of several (triphos)Pt-aryl$^+$ establishes the first example of aryl–F coupling from a Pt center.

The demand for organofluorine compounds has stimulated much recent effort to develop metal mediated fluorination reactions.[1] Despite the versatility of available C–X (X = C, N, O, S, Cl, Br, I, *etc.*) coupling methodologies,[2] C–F couplings *via* reductive elimination remain challenging.[1d,f] Metal catalyzed C–F couplings that utilize fluoride sources encounter additional challenges due to the intrinsically low polarizability and nucleophilicity, pronounced hydration power, and high basicity of F^-. Nevertheless, several notable $Pd^{0/II}$ catalyzed nucleophilic fluorinations have been recently reported.[3] More fruitful have been recent metal-catalyzed *electrophilic* fluorination reactions,[5–8] wherein high-valent metal fluoro intermediates (*e.g.* Pd(IV),[4] Ag(II)···Ag(II),[5] Au(III),[6] *etc.*) are more prone to productive reactivity, including C–H activation, cross-coupling, and C–F reductive elimination.[1f,7]

To explore Pt analogues of these *electrophilic* reactions, we recently demonstrated a system that efficiently fluorinates Pt–C_{sp^3} bonds.[8b] As illustrated in eqn (1), wherein PPP = bis(2-diphenylphosphinoethyl)phenylphosphine (*i.e.*, triphos), the C–F coupling proved to be stereoretentive and was proposed to occur by concerted reductive elimination of a putative dicationic Pt(IV)–F intermediate (**A**). The reaction was accelerated by increased steric congestion around Pt,[8b] however, information on the short-lived Pt(IV)–F species was lacking.



(1)

Sp^2-carbon–halogen bond forming reactions from Pt(IV) centers are rare,[1g,9,10] with the few known examples restricted to C–I and C–Br couplings.[11] Extending our efforts on Pt–C bond fluorination reactions, we have examined the electrophilic fluorination of (triphos)Pt-*aryl*$^+$ complexes. Herein, we report these reactions and provide evidence that supports the intermediacy of Pt(IV)–F complexes in the C–F reductive coupling reaction.

Complexes **1–4** were synthesized by ligand displacement of (COD)PtAr(X) (COD = cycloocta-1,5-diene, X = Cl, or I) with triphos, followed by salt metathesis with $NaBF_4$.[12,13] Complex **5** was prepared by treating chloro(2-phenylpyridine)[2-(2-pyridyl)-phenyl-C,N]Pt[14] with triphos, while its dicationic isostere **6** was obtained by reacting [(triphos)Pt(NCC_6F_5)]$(BF_4)_2$[15] with 2-phenylpyridine.[12]

These compounds were characterized by NMR and HRMS, with the molecular structure of **4**§ being verified by X-ray analysis (Fig. 1).[12] Consistent with the solid state structure of **4**, NOESY analysis suggested that the *ortho*-substituent in **2**, **4–6** preferentially oriented *syn* to the central P-*Ph* group of the triphos ligand. While **2**, **4**, **5** and **6** exist exclusively in this *syn*-rotamer, both *syn*- and *anti*-forms (2.7 : 1) were observed for **3**.[12] The preference for the *syn*- over the *anti*-form suggests that the face of the square plane containing the apical P-*Ph* group is *less* congested and may be more kinetically accessible.

When subjected to electrophilic fluorination conditions, these (triphos)Pt-*aryl*$^+$ complexes were found to be much less reactive than their Pt-*alkyl*$^+$ analogs.[8b] When screening common "F^+" sources including *N*-fluorobenzenesulfonimide, several *N*-fluoro-pyridinium salts, Selectfluor® and XeF_2, only the latter two exhibited reasonable reactivity with **1**, for which the optimal solvent was identified to be acetonitrile. ^{31}P and ^{19}F NMR spectroscopy proved most advantageous for *in situ* monitoring

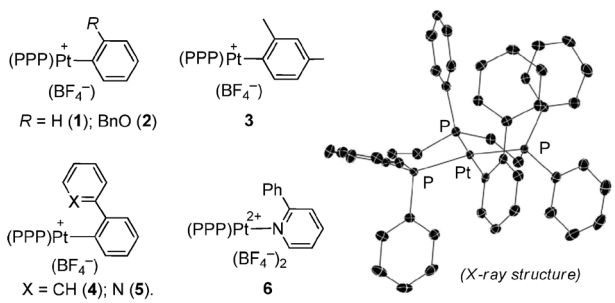


Fig. 1 Left: complexes **1–6**; right: X-ray structure of **4** (H atoms and BF_4^- anion are omitted for clarity).

[a] *Caudill Laboratories, Department of Chemistry, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3290, USA. E-mail: mgagne@unc.edu*
[b] *Department of Chemistry, Queen's University, Kingston, ON K7L 3N6, Canada*
[c] *U.S. Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709, USA*

† Electronic supplementary information (ESI) available: Experimental details, characterization data, and complete X-ray diffraction data. CCDC 838071–838073. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c1cc15006e

‡ The author to whom inquiries on the X-ray structures should be directed.

of these reactions and Selectfluor® proved to be cleaner and more productive than XeF_2.

With **1**, a complex mixture of phenyl Pt(IV)–F species was obtained upon reacting with XeF_2 (RT, <20 min). By contrast, Selectfluor® provided one main phenyl Pt(IV)–F complex (RT, ~2 h) (δ_F = −360.3 ppm, J_{Pt-F} = 1453 Hz).[12] These Pt(IV)–F species, however, failed to reductively eliminate PhF even after prolonged heating (80 °C, >30 h).

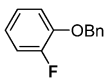
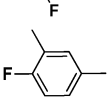
The *ortho*-substituents considerably slowed down the reactions of **2** and **3** with XeF_2 and Selectfluor®, however, their presence proved beneficial for achieving the desired sp^2 C–F coupling. In the case of **2**, XeF_2 provided one major Pt(IV)–F complex (δ = −352.8 ppm, J_{Pt-F} = 1442 Hz) in ~75% NMR yield (RT, 12 h).[12] However, the precise structure of this product remains unclear, as all attempts to crystallize it failed and spectroscopic data were not conclusive. Heating a freshly prepared reaction mixture containing this Pt(IV)–F complex at 80 °C led to only traces of the aryl–F coupling product (<5% GC-MS yield). Similar results were obtained when directly reacting **2** with XeF_2 at 80 °C. In contrast, reactions of **3** with XeF_2 (RT, 15 h) directly generated a substantial amount of the aryl–F coupling product 1-fluoro-2,4-dimethylbenzene (~55% NMR yield), along with the corresponding $[(triphos)Pt\text{-}NCMe]^{2+}$ by-product. The formation of a Pt(IV)–F complex (δ_F = −351.9 ppm, J_{Pt-F} = 1146 Hz) in ~25% NMR yield and other unidentified Pt species was also observed.[12] To our knowledge, this reaction represents the first example of aryl–F coupling from a Pt center.

Despite being unreactive at RT, Selectfluor® readily fluorinated **2** and **3** at 80 °C to produce the aryl fluoride;[12] no Pt(IV)–F species was observable during *in situ* monitoring of these reactions. These results are summarized in Table 1.

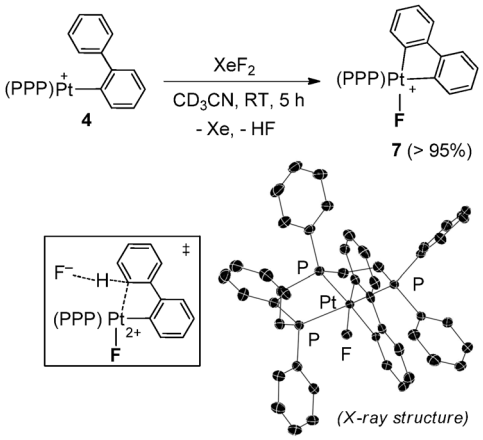
Surprisingly, the reaction of **4** with XeF_2 preferentially yielded the *ortho*-cyclometalated complex **7** (Scheme 1). NMR monitoring of the reaction revealed its gradual conversion to the Pt(IV)–F complex, **7**§, which was characterized by NMR, HRMS and X-ray diffraction.[12] In contrast to the aforementioned Pt(IV)–F species, this complex exhibits a ^{19}F NMR resonance at δ = −299.9 ppm with a considerably diminished ^{195}Pt–^{19}F coupling (~173 Hz).

As shown in Scheme 1, the Pt center in **7** adopts an octahedral coordination geometry, with the Pt–F bond (2.099(2) Å) oriented *anti* to the central P-*Ph* group of the triphos ligand, and the biphenyl moiety adopting a *C,C′*-chelating mode. Similar cyclometalation of an *ortho* sp^2-C–H bond was previously noted upon fluorinating (triphos)Pt-CH_2Ph^+ with XeF_2

Table 1 Fluorination of complexes **1–3** with Selectfluor®[a]

Complex	Product	Time	NMR yield[b] (%)
1	$[(PPP)Pt^{IV}(Ph)(\mathbf{F})]^{2+}$	<20 min	60–70
2		1 h	91
3		2 h	>95

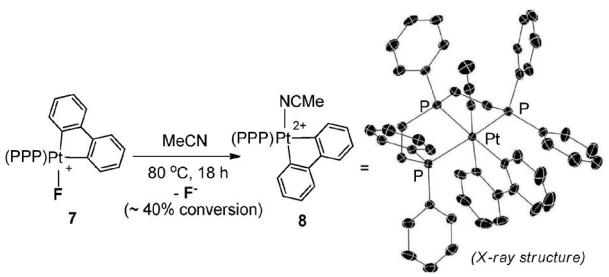
[a] Conditions: complexes **1–3** (0.02 mmol), 1.5 equiv. of Selectfluor®, dry CD_3CN (0.5 mL), 80 °C. [b] Mass balance: structurally unidentified organometallic Pt species.



Scheme 1 Generation of complex **7**; inset: X-ray structure of **7** (H atoms and anion are omitted for clarity).

in melting acetonitrile.[8b] This reactivity mode apparently reflects the intermediacy of Pt(IV) fluorides in both cases.[8b] The propensity of Pt(IV) and Pd(IV) centers in metalating aromatic C–H bonds has been demonstrated and exploited recently in several coupling strategies.[7,8a]

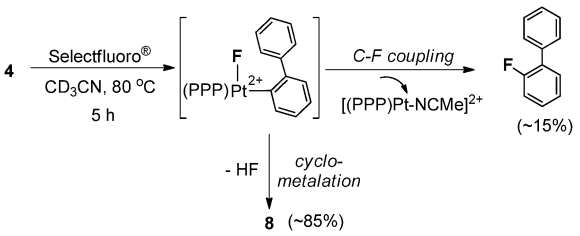
Heating an acetonitrile solution of **7** at 80 °C resulted in slow F^- extrusion and the concomitant formation of a dicationic Pt(IV)–MeCN adduct, **8** (eqn (2)). No C–F reductive elimination was observed during the process, and X-ray diffraction§ revealed that the MeCN ligand coordinates *syn* to the triphos ligand's central P-*Ph* group (eqn (2)).[12] Consistent with the increase in the net charge of the Pt(IV) center are large downfield shifts of the ^{31}P NMR signals as compared to **7** (*e.g.*, $\Delta\delta$ = +22.7 ppm for the central P) and ^1H NMR signals of the biphenyl moiety.



(2)

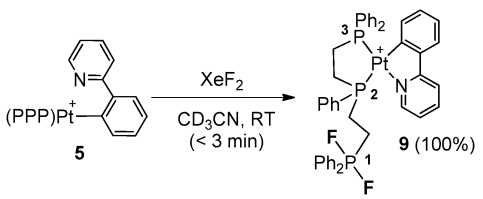
In addition to **7**, reactions of **4** with XeF_2 at RT (Scheme 1) also yielded traces of **8** (<5%).[12] By contrast, reactions of **4** with Selectfluor® directly provided **8** (85%, ~5 h), along with 15% of 2-fluorobiphenyl and the corresponding $[(triphos)Pt\text{-}NCMe]^{2+}$ (Scheme 2).[12] We reason that the formation of both **7** and **8** implies the presence of Pt(IV) intermediates.

The contrasting outcomes for reactions of **2–4** with XeF_2 and Selectfluor® presumably stem from the presence of a basic fluoride anion in the former case, though a size difference in the "F^+" source is also conceivable.[16] Shown in Scheme 1 is one way wherein F^- could accelerate *ortho*-metalation *vs.* reductive elimination. Since the two Pt(II) faces were shown to be sterically different, it is also possible that these reactions evolve differently based on which face F^+ attacks.[16] Recently, Vigalok and co-workers have also reported an F^+ reagent-dependent reaction behavior when fluorinating Pt-aryl complexes.[8a]



Scheme 2 Competitive cyclometalation and C–F coupling pathways.

To gain more insights into the Pt(IV)–F species proposed in Schemes 1 and 2, the fluorination of **5** and **6** by XeF_2 was examined. In particular, we hoped that the *ortho*-pyridyl group in **5** could trap the coordinatively unsaturated Pt(IV)–F intermediate. Instead, XeF_2 converted **5** into the Pt(II) complex **9** (eqn (3)), whose configuration was deduced from ^{31}P NMR data (*e.g.*, $\delta_F = -37.9$ ppm, $J_{P1\text{-}F} = 652$ Hz; $J_{Pt\text{-}P3} = 3745$ Hz *vs.* $J_{Pt\text{-}P2} = 1863$ Hz).[12] The formation of this complex presumably occurred *via* associative displacement of one triphos phosphine arm (P_1, eqn (3)) in **5** by the pyridyl ligand, followed by oxidation of the unligated phosphine ligand. We have previously shown that phosphine fluorination by XeF_2 is rapid.[8b] Despite its structural analogy to **4** and **5**, complex **6** failed to react with XeF_2, indicating that a dicationic Pt(II) center may be too electron deficient to generate a tricationic Pt(IV) structure.



(3)

In summary, we report the first sp^2 C–F coupling from a Pt center. Like Pt–C_{sp^3} bonds, steric congestion is a key factor, as is F^+ source. We have also demonstrated that *ortho*-metalation may be competitive with C–F reductive elimination. The intermediacy of Pt(IV)–F complexes, the product of direct F^+ addition to Pt(II), is supported by the direct spectroscopic observation of several Pt(IV)–F species and the isolation of *ortho*-metalation products.

We acknowledge the generous support of the NIH (GM-60578) and Army Research Office Staff Research Program. SZ thanks NSERC of Canada for a Postdoctoral Fellowship.

Notes and references

§ X-Ray structure data: complex **4** (CCDC 838071), $C_{47}H_{44}BCl_2F_4P_3Pt$, $M = 1054.53$, *monoclinic*, space group $P2_1/c$, $a = 11.1844(10)$ Å, $b = 15.4199(2)$ Å, $c = 24.7809(3)$ Å, $\alpha = \gamma = 90°$, $\beta = 91.93(1)°$, $V = 4271.35(8)$ Å^3, $Z = 4$, $T = 100(2)$ K, 36 354 collected reflections, 8252 unique reflections ($R_{int} = 0.0182$); $R_1 = 0.0241$, $wR_2 = 0.0604$ for data with $I > 2\sigma(I)$, and $R_1 = 0.0245$, $wR_2 = 0.0607$ for all unique data. Complex **7** (CCDC 838072), $C_{49}H_{48}BF_5NO_2P_3Pt$, $M = 1076.69$, *monoclinic*, space group $C2/c$, $a = 31.7695(19)$ Å, $b = 10.0332(6)$ Å, $c = 33.988(3)$ Å, $\alpha = \gamma = 90°$, $\beta = 116.680(1)°$, $V = 9680.2(12)$ Å^3, $Z = 8$, $T = 180(2)$ K, 18 908 collected reflections, 9401 unique reflections ($R_{int} = 0.0255$); $R_1 = 0.0302$, $wR_2 = 0.0685$ for data with $I > 2\sigma(I)$, and $R_1 = 0.0374$, $wR_2 = 0.0707$ for all unique data. Complex **8** (CCDC 838073), $C_{48}H_{46.75}BF_{9.50}NO_{1.38}P_{3.50}Pt$, $M = 1154.41$, *triclinic*, space group $P\bar{1}$, $a = 13.666(1)$ Å, $b = 17.484(2)$ Å, $c = 22.340(2)$ Å, $\alpha = 95.002(1)°$, $\beta = 113.180(1)°$, $\gamma = 96.172(1)°$, $V = 4829.3(8)$ Å^3, $Z = 4$, $T = 180(2)$ K, 18 829 collected reflections, 18 829 unique reflections ($R_{int} = 0.0454$); $R_1 = 0.0339$, $wR_2 = 0.0841$ for data with $I > 2\sigma(I)$, and $R_1 = 0.0483$, $wR_2 = 0.0876$ for all unique data.

1 (*a*) T. Hiyama, *Organofluorine Compounds*, Springer, Berlin, 2000; (*b*) K. Müller, C. Faeh and F. Diederich, *Science*, 2007, **317**, 1881; (*c*) K. L. Kirk, *Org. Process Res. Dev.*, 2008, **12**, 305; (*d*) V. V. Grushin, *Acc. Chem. Res.*, 2010, **43**, 160; (*e*) T. Furuya, C. A. Kuttruff and T. Ritter, *Curr. Opin. Drug Discovery Dev.*, 2008, **11**, 803; (*f*) T. Furuya, A. S. Kamlet and T. Ritter, *Nature*, 2011, **473**, 470; (*g*) A. Vigalok, *Organometallics*, 2011, **30**, 4802.

2 J. F. Hartwig, *Organometallic Metal Chemistry*, University Science Books, Sausalit, CA, 2010, ch. 19.

3 For recent examples of metal-catalyzed nucleophilic fluorinations, see: (*a*) D. A. Watson, M. Su, G. Teverovskiy, Y. Zhang, J. García-Fortanet, T. Kinzel and S. L. Buchwald, *Science*, 2009, **325**, 1661; (*b*) M. H. Katcher and A. G. Doyle, *J. Am. Chem. Soc.*, 2010, **132**, 17402; (*c*) C. Hollingworth, A. Hazari, M. N. Hopkinson, M. Tredwell, E. Benedetto, M. Huiban, A. D. Gee, J. M. Brown and V. Gouverneur, *Angew. Chem., Int. Ed.*, 2011, **50**, 2613.

4 For recent examples of C–F couplings through Pd(IV) intermediates, see: (*a*) K. L. Hull, W. Q. Anani and M. S. Sanford, *J. Am. Chem. Soc.*, 2006, **128**, 7134; (*b*) T. Furuya, H. M. Kaiser and T. Ritter, *Angew. Chem., Int. Ed.*, 2008, **47**, 5993; (*c*) T. Furuya and T. Ritter, *J. Am. Chem. Soc.*, 2008, **130**, 10060; (*d*) N. D. Ball and M. S. Sanford, *J. Am. Chem. Soc.*, 2009, **131**, 3796; (*e*) X. Wang, T. S. Mei and J. Q. Yu, *J. Am. Chem. Soc.*, 2009, **131**, 7520; (*f*) T. Wu, G. Yin and G. Liu, *J. Am. Chem. Soc.*, 2009, **131**, 16354; (*g*) T. Furuya, D. Benitez, E. Tkatchouk, A. E. Strom, P. Tang, W. A. Goddard III and T. Ritter, *J. Am. Chem. Soc.*, 2010, **132**, 3793; (*h*) W. Wang, J. Jasinski, G. B. Hammond and B. Xu, *Angew. Chem., Int. Ed.*, 2010, **49**, 7247.

5 For Ag(I)-catalyzed *electrophilic* fluorination reactions, see: (*a*) T. Furuya, A. E. Strom and T. Ritter, *J. Am. Chem. Soc.*, 2009, **131**, 1662; (*b*) T. Furuya and T. Ritter, *Org. Lett.*, 2009, **11**, 2860; (*c*) P. Tang, T. Furuya and T. Ritter, *J. Am. Chem. Soc.*, 2010, **132**, 12150; (*d*) T. Xu, X. Mu, H. Peng and G. Liu, *Angew. Chem., Int. Ed.*, 2011, **50**, 8176.

6 J. A. Akana, K. X. Bhattacharyya, P. Müller and J. P. Sadighi, *J. Am. Chem. Soc.*, 2007, **129**, 7736.

7 For a review on the use of F^+ to enable coupling and activation reactions from high-valent metal centers, see: K. M. Engle, T.-S. Mei, X. Wang and J.-Q. Yu, *Angew. Chem., Int. Ed.*, 2011, **50**, 1478.

8 (*a*) A. W. Kaspi, I. Goldberg and A. Vigalok, *J. Am. Chem. Soc.*, 2010, **132**, 10626; (*b*) S.-B. Zhao, J. J. Becker and M. R. Gagné, *Organometallics*, 2011, **30**, 3926.

9 (*a*) A. Vigalok, *Chem.–Eur. J.*, 2008, **14**, 5102; (*b*) A. W. Kaspi and A. Vigalok, *Top. Organomet. Chem.*, 2010, **31**, 19.

10 For recent examples of sp^3-carbon–halogen bond forming reactions from Pt(IV) centers, see: (*a*) K. I. Goldberg, J. Yan and E. L. Winter, *J. Am. Chem. Soc.*, 1994, **116**, 1573; (*b*) K. I. Goldberg, J. Yan and E. M. Breitung, *J. Am. Chem. Soc.*, 1995, **117**, 6889; (*c*) S.-B. Zhao, R.-Y. Wang and S. Wang, *Organometallics*, 2009, **28**, 2572; (*d*) P. F. Oblad, J. E. Bercaw, N. Hazari and J. A. Labinger, *Organometallics*, 2010, **29**, 789.

11 (*a*) R. Ettorre, *Inorg. Nucl. Chem. Lett.*, 1969, **5**, 45; (*b*) A. Yahav-Levi, I. Goldberg, A. Vigalok and A. N. Vedernikov, *J. Am. Chem. Soc.*, 2008, **130**, 724; (*c*) A. Yahav-Levi, I. Goldberg, A. Vigalok and A. N. Vedernikov, *Chem. Commun.*, 2010, **46**, 3324.

12 See ESI† for details.

13 Although not discussed herein, the reaction of (COD)Pt(*mesityl*)(I) with triphos triggers migratory insertion of the Pt–*mesityl* bond into the COD moiety; the product was crystallographically characterized, see: S.-B. Zhao, R.-Y. Wang and M. R. Gagné, *Acta Crystallogr., Sect. E: Struct. Rep. Online*, 2011, **E67**, m972.

14 N. Godbert, T. Pugliese, I. Aiello, A. Bellusci, A. Crispini and M. Ghedini, *Eur. J. Inorg. Chem.*, 2007, **32**, 5105.

15 J. H. Koh and M. R. Gagné, *Angew. Chem., Int. Ed.*, 2004, **43**, 3459.

16 Being linear, XeF_2 is significantly smaller than Selectfluor®.