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Electrophilic fluorination of cationic Pt-aryl complexes†

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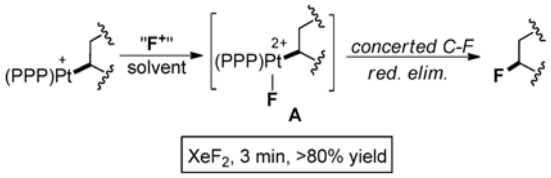
Abstract

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)

†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

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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*-fluoropyridinium 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 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=

§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, $\alpha = \gamma = 90°$, β = 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, $\alpha = \gamma = 90°$, β = 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, α = 95.002(1)°, β = 113.180(1)°, γ = 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.

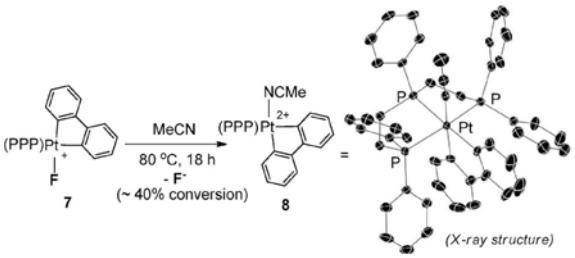
−351.9 ppm, $J_{Pt–F}$=1146 Hz) in~25%NMR yield and other unidentified Pt species was also observed.[12] To our knowledge, this reaction represents the first example of aryl–F coupling from a Pt center.

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 byNMR, HRMSand 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 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.



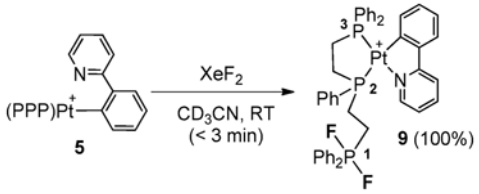
(2)

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]

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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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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: Zhao S-B, Wang R-Y, Gagné MR. Acta Crystallogr, Sect E: Struct Rep Online. 2011; E67:m972.
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16. Being linear, XeF_2 is significantly smaller than Selectfluor®.

†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

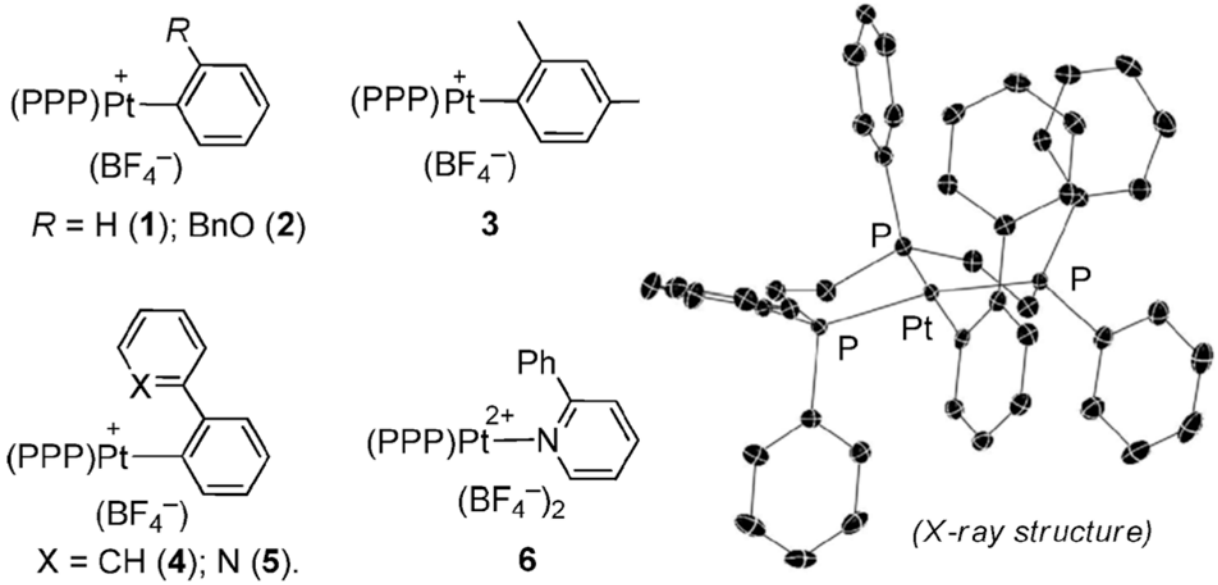
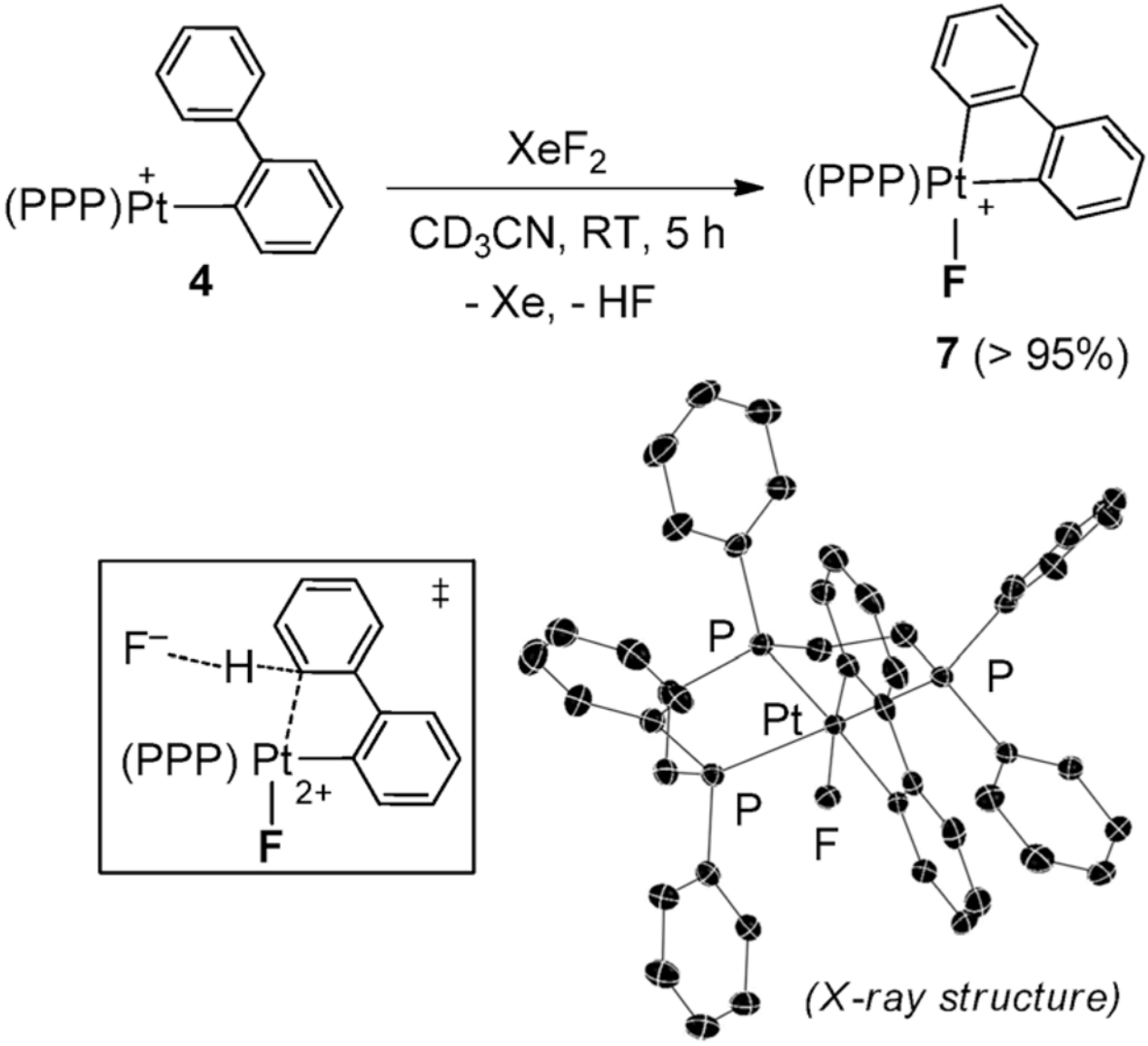
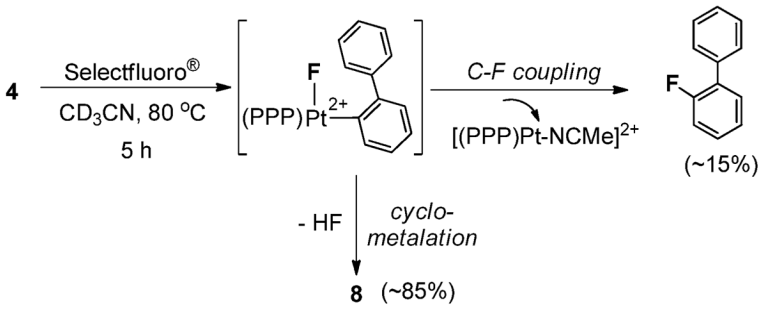


Fig. 1.
Left: complexes **1**–**6**; right: X-ray structure of **4** (H atoms and BF^{4-} anion are omitted for clarity).



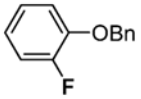
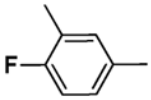
Scheme 1.
Generation of complex **7**; inset: X-ray structure of **7** (H atoms and anion are omitted for clarity).



Scheme 2.
Competitive cyclometalation and C–F coupling pathways.

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.