

Aryl-CF₃ Bond-Forming Reductive Elimination from Palladium(IV)

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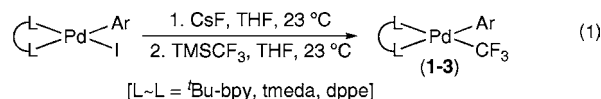
Trifluoromethyl groups feature prominently in a wide variety of medicinal compounds.¹ The substitution of CH₃ for CF₃ can dramatically change the physical properties and biological activity of organic molecules. As a result, tremendous effort has been directed at the introduction of CF₃ groups into organic structures.² This has led to numerous methods for the efficient construction of sp³ carbon-CF₃ bonds using nucleophilic (CF₃⁻), electrophilic (CF₃⁺), and radical (CF₃•)-based trifluoromethylating reagents.²

In contrast, the formation of aryl carbon-CF₃ bonds remains significantly more challenging.³ This functional group is commonly prepared using the Swarts reaction (which requires high temperatures and reactive SbF₅)⁴ or through the use of stoichiometric quantities of ill-defined and sensitive “Cu-CF₃” reagents.⁵ Transition metal catalyzed cross-coupling would provide a highly attractive alternative route to aryl-CF₃ linkages. While sporadic reports have suggested the viability of this approach,⁶ general, efficient, and robust versions of such transformations have been slow to develop. The major challenge in this area is that CF₃ ligands are typically inert toward C-C bond-forming reductive elimination.⁷

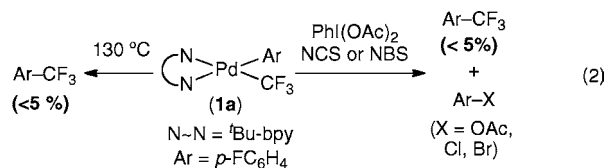
Several groups have made exciting recent progress toward addressing this challenge. For example, Vicic and co-workers have shown that the isolable *N*-heterocyclic carbene (NHC) copper complexes (NHC)Cu-CF₃ react stoichiometrically with aryl iodides to afford Ar-CF₃ products.⁸ Vicic’s group has also established that (dippe)Ni^{II}(Ph)(CF₃) undergoes H₂O-promoted Ph-CF₃ coupling in modest (22%) yield.⁹ Finally, Grushin has demonstrated stoichiometric Ph-CF₃ coupling from (Xantphos)Pd^{II}(Ph)(CF₃).¹⁰ This latter work is the only reported example of selective Ar-CF₃ bond-forming reductive elimination from a well-defined transition metal aryl/CF₃ complex. However, this reaction was limited to Ar = Ph and was also extremely sensitive to the nature of the ancillary ligand at Pd^{II}. A variety of P- and N-donor ligands including dppe,¹¹ dppb,¹¹ tmeda,¹¹ and PPh₃ were examined,^{10,12} but only Xantphos was effective at promoting this transformation below 150 °C. Thus, the development of complementary and more general strategies for arene trifluoromethylation from M(Ar)(CF₃) species remains a topic of great current interest.

Our group¹³ and others¹⁴ have shown that Pd^{IV} complexes can participate in reductive elimination reactions that are challenging at other metal centers. Since high oxidation state palladium can be accessed following arene C-H activation¹⁵ or transmetalation¹⁶ processes, Ar-CF₃ coupling through this manifold would provide opportunities for the development of diverse new trifluoromethylation reactions. We report herein the first demonstration of Ar-CF₃ bond-forming reductive elimination from a Pd^{IV}(Ar)(CF₃) complex.

Our studies began with the synthesis of a series of new palladium(II) complexes of general structure (L)₂Pd^{II}(Ar)(CF₃) (**1–3**).^{12b} These were prepared by treating the corresponding Pd^{II} aryl iodides with CsF followed by TMSCF₃ at 23 °C in THF (eq 1).^{10,12} The products were obtained in 32–76% yield as yellow solids (see Supporting Information for full details).

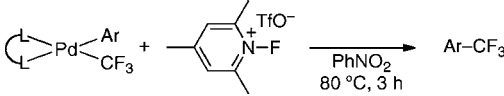


Heating complexes **1–3** at 130 °C for 3 d in nitrobenzene-*d*₅ produced <5% of Ar-CF₃ coupling products (eq 2). This is consistent with literature reports showing that most Pd^{II}(Ar)(CF₃) complexes are poorly reactive toward Ar-CF₃ bond-forming reductive elimination.^{10,12} We reasoned that 2e⁻ oxidation should yield Pd^{IV} species that might undergo more facile Ar-CF₃ coupling.^{13–15} However, treatment of **1a** with PhI(OAc)₂, NCS,¹¹ or NBS¹¹ (oxidants known to promote the oxidation of Pd^{II} to Pd^{IV})¹³ did not afford 1-fluoro-4-trifluoromethylbenzene; instead, the corresponding acetoxyated or halogenated products were obtained (eq 2). This result suggests that Ar-X (X = OAc, Cl, Br) bond-forming reductive elimination is significantly faster than Ar-CF₃ coupling in this system.



We next examined the use of *N*-fluoro-2,4,6-trimethylpyridinium triflate (NFTPT) to effect Ar-CF₃ coupling from **1a**. This oxidant was selected based on the hypothesis that fluoride and triflate (the X-type ligands introduced to a putative Pd^{IV} intermediate by NFTPT) might undergo slower reductive elimination than CF₃.^{17,18} Gratifyingly, treatment of **1a** with NFTPT at 80 °C for 3 h in nitrobenzene-*d*₅ resulted in clean formation of 1-fluoro-4-trifluoromethylbenzene in 85% yield (as determined by ¹⁹F NMR spectroscopy) (Table 1, entry 1). As predicted, <5% of products derived from C-F or C-OTf coupling were observed. NFTPT also promoted Ar-CF₃ bond formation from the other Pd^{II} complexes **1b–3** (Table 1). These transformations were efficient with strongly electron-donating and electron-withdrawing arene substituents (entries 2 and 3, respectively). In contrast, reactions of [Cu-CF₃] are often highest yielding with electron-deficient aryl coupling partners.⁶ Additionally, unlike Grushin’s Ar-CF₃ coupling from Pd^{II} (which is very sensitive to the nature of the ancillary ligands),¹⁰ this oxidatively induced transformation proceeded in modest to excellent yield with diverse N- and P-donor ligands, including ^tBu-bpy, tmeda, and dppe.¹¹

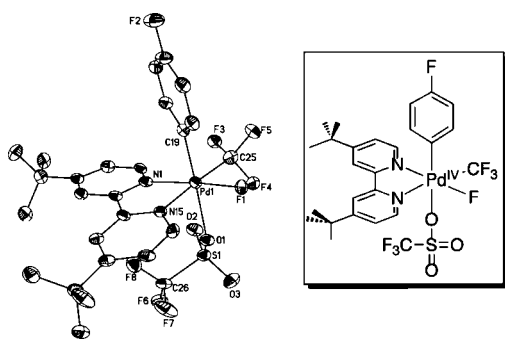
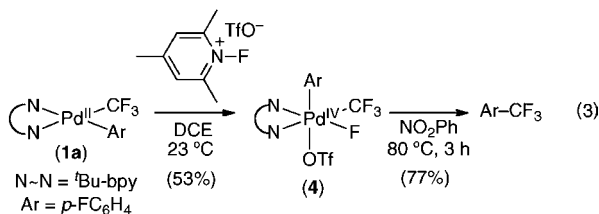
In an effort to detect intermediates in the Ar-CF₃ coupling process, we examined the reaction of **1a** with NFTPT at room temperature. In both nitrobenzene and DCE, a single major palladium-containing product (**4**) was observed. This species was isolated from DCE in 53% yield, and the analytically pure yellow solid exhibits four ¹⁹F NMR signals in a 3:3:1:1 ratio. X-ray quality crystals were obtained by vapor diffusion of pentanes into a DCE

Table 1. Oxidatively Induced Ar–CF₃ Coupling from Complexes 1–3


Entry	Compound	L ₂	Ar	Yield Ar–CF ₃ ^a
1	1a	^t Bu-bpy	<i>p</i> -FC ₆ H ₄	85%
2	1b	^t Bu-bpy	<i>p</i> -CF ₃ C ₆ H ₄	61%
3	1c	^t Bu-bpy	<i>p</i> -CH ₃ OC ₆ H ₄	86%
4	1d	^t Bu-bpy	<i>p</i> -PhC ₆ H ₄	83%
5	1e	^t Bu-bpy	<i>p</i> -CH ₃ C ₆ H ₄	85%
6	2	tmeda	<i>p</i> -FC ₆ H ₄	89%
7	3	dppe	Ph	29%

^a Determined by ¹⁹F NMR spectroscopy.

solution of **4**. The X-ray crystal structure is shown in Figure 1 and confirms that **4** is the octahedral Pd^{IV} species (^tBu-bpy)-Pd^{IV}(CF₃)(F)(OTf)(C₆H₄F). To our knowledge this is the first isolated example of a Pd^{IV} complex containing a perfluoroalkyl ligand.¹⁹

**Figure 1.** ORTEP Diagram of **4**.

The reactivity of **4** toward Ar–CF₃ bond formation was next investigated. Heating a nitrobenzene-*d*₅ solution of **4** at 80 °C for 3 h resulted in smooth reductive elimination to form 1-fluoro-4-trifluoromethylbenzene in 77% yield (eq 3). Similar to the reactions in Table 1, none of the products derived from Ar–F or Ar–OTf coupling were observed by ¹⁹F NMR spectroscopy. This result demonstrates for the first time that Ar–CF₃ coupling can be kinetically accessible from mono-*o*-aryl Pd^{IV} complexes; as such, it provides an attractive conceptual framework for the development of Pd^{II/IV}-catalyzed arene trifluoromethylation reactions.

In summary, we describe herein a new Ar–CF₃ bond-forming reaction mediated by Pd^{IV} centers. These transformations proceed

under mild conditions with diverse nitrogen- and phosphorus-based ancillary ligands. Efforts to gain further insights into the mechanism as well as to develop related catalytic transformations are currently underway in our laboratory and will be reported in due course.

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Supporting Information Available: Experimental and crystallographic details and spectroscopic data for new compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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