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# Palladium-Catalyzed Homocoupling of Highly Fluorinated Arylboronates: Studies of the Influence of Strongly vs. Weakly Coordinating Solvents on the Reductive Elimination Process

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**ABSTRACT:** C–C reductive elimination from  $[PdL_2(C_6F_5)_2]$  to form polyfluorinated biaryls has been a challenge for over 50 years. Thus, palladium-catalyzed homocoupling of arylboronates (Ar<sub>F</sub>–Bpin) containing two *ortho*-fluorine substituents is very difficult as the reaction typically stops at the  $[PdL_2(Ar_F)_2]$  stage after two transmetalation steps. The transmetalated complexes *cis*- $[Pd(MeCN)_2(C_6F_5)_2]$  (**3a**), *cis*- $[Pd(MeCN)_2(2,4,6-C_6F_3H_2)_2]$  (**3b**), and *cis*- $[Pd(MeCN)_2(2,6-C_6F_2H_3)_2]$ (**3e**) have been isolated from the reaction of Ar<sub>F</sub>–Bpin with Pd(OAc)\_2 in acetonitrile solvent, with no homocoupling observed. However, catalytic homocoupling proceeds smoothly in a "weaklycoordinating" arene solvent as long as no ancillary ligands or coordination solvents are present. DFT computations performed reveal that the active catalyst formed by arene solvent coordination leads to an overall reduced barrier for the reductive elimination step compared to the formation of stable  $[PdL_2(Ar_F)_2]$  complexes in the presence of a donor ligand or solvent L. Many transition metal-catalyzed processes consist of steps such as oxidative addition, reductive elimination, migratory insertion, transmetalation, and  $\beta$ -hydride elimination.<sup>1</sup> Reductive elimination is often important for the final product-releasing step. Generally, two electronic effects have been observed for the reductive elimination from the [ML<sub>2</sub>(Ar)(Ar')] complexes containing group-10 metals. As the metal is formally reduced in the process, reductive elimination of Ar-Ar' from these complexes is usually faster if the ancillary ligand L is only weakly electron donating or strongly  $\pi$ accepting.<sup>2</sup> Furthermore, the rates of reductive elimination from these complexes are higher when an electron-rich and an electron-poor aryl group are involved in the reaction compared to two electronrich aryl groups. The slowest reductive elimination rate steps are typically found when both aryl groups are electron-poor.<sup>2</sup> In particular, [PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] complexes are well known for their high stability and, thus, reluctantly undergo reductive elimination,<sup>3</sup> due to their strong Pd–Ar bonds.<sup>3g,h</sup> Consequently, palladium-catalyzed homocoupling of C<sub>6</sub>F<sub>5</sub>B(OR)<sub>2</sub>,<sup>4</sup> and Suzuki-Miyaura crosscoupling of C<sub>6</sub>F<sub>5</sub>B(OR)<sub>2</sub> with 2,6-C<sub>6</sub>F<sub>2+n</sub>H<sub>3-n</sub>X are found to be difficult.<sup>5</sup> For example, Oliveira *et al.* reported optimized conditions for the Pd-catalyzed homocoupling of Ar-BF<sub>3</sub>K in an aqueous solvent which leads to coupled products in good to very good yields.<sup>4</sup> Notably, if the substrates have two ortho-fluorine substituents, e.g., C<sub>6</sub>F<sub>5</sub>BF<sub>3</sub>K or 2,6-C<sub>6</sub>F<sub>2</sub>H<sub>3</sub>BF<sub>3</sub>K, the corresponding homocoupling products were not observed.<sup>4</sup> Regarding Suzuki-Miyaura cross-coupling, Osakada et al.<sup>5b</sup> reported the reaction of 2,4,6-trifluorophenylboronic acid with trans-[Pd(PEt<sub>3</sub>)<sub>2</sub>( $C_6F_5$ )I] in the presence of Ag<sub>2</sub>O in toluene/H<sub>2</sub>O which led to the formation of a stable intermediate *trans*-[Pd(PEt<sub>3</sub>)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)(2,4,6-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>)] and no reductive elimination was observed.

As early as in 1970, Rausch and Tibbets reported the synthesis of  $[PdL_2(C_6F_5)_2]$  (L = PPh<sub>2</sub>Me; L<sub>2</sub> = bpy)<sup>3f</sup> and, in 1964 and 1965, Rosevear and Stone reported that  $[NiL_2(C_6F_5)_2]$  (L = PEt<sub>3</sub>, PPh<sub>3</sub>; L<sub>2</sub> = bpy)<sup>6</sup> and  $[PtL_2(C_6F_5)_2]$  (L = PEt<sub>3</sub>, PPh<sub>3</sub>; L<sub>2</sub> = dppe)<sup>7</sup> are stable complexes. Jones *et al.*<sup>8a</sup> and Perutz *et al.*<sup>8b,c</sup> reported that a high M–Ar bond energy can be achieved when two *ortho*-fluorine substituents are present on the aryl group. Thus, as long as the two aryl groups contain two *ortho*-fluorine substituents,  $[PdL_2(Ar_F)_2]$  complexes are stable, e.g.,  $[PdL_2(C_6F_4(4-C_5H_{10}N))_2]$  (L<sub>2</sub> = dppe, cod)<sup>9</sup> and  $[PdL_2(2,4,6-C_6F_3H_2)_2]$  (L = PhCN, PEt<sub>3</sub>, AsPh<sub>3</sub>, P(OMe)<sub>3</sub>, P(OEt)<sub>3</sub>, P(OPh)<sub>3</sub>; L<sub>2</sub> = cod, tmen)<sup>10</sup>.





Due to the high stability of  $[PdL_2(C_6F_5)_2]$  complexes, researchers were encouraged to develop efficient methods to enhance the rate of the reductive elimination step (Scheme 1). In 2008, Yamamoto *et al.* demonstrated that addition of a Brønsted acid, HNO<sub>3</sub>, promotes the reductive elimination of C<sub>6</sub>F<sub>5</sub>–C<sub>6</sub>F<sub>5</sub> from *cis*-[PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (L<sub>2</sub> = cod, bpy, and dppb).<sup>3g</sup> Although this strategy is successful under stoichiometric conditions, it is not compatible with the catalytic homocoupling of arylboronates, as basic reagents are required to activate Ar–B(OR)<sub>2</sub> for transmetalation to the Pd center.<sup>11</sup>

In 2016, Espinet *et al.*<sup>12</sup> reported that reductive elimination of  $C_6F_5-C_6F_5$  from *cis*-[Pd(THF)<sub>2</sub>( $C_6F_5$ )<sub>2</sub>] could be promoted by introduction of phosphine ligands, (P*t*Bu<sub>3</sub>, *o*-TolPEWO-F, *t*BuXPhos, P( $C_6F_5$ )<sub>3</sub>, PhPEWO-F, P(*o*-Tol)<sub>3</sub>, *t*BuBrettPhos, Xantphos, and PhPEWO-H), in toluene solvent. They suggested that immediate reductive elimination to form  $C_6F_5$ – $C_6F_5$  occurred after rapid ligand substitution. Among different phosphines examined for efficient stoichiometric reductive elimination,  $PtBu_3$  was ranked as the best ligand according to initial coupling rates.

In 2017, Alcarazo *et al.*<sup>3h</sup> attempted to solve the problem by synthesizing  $[PdL_2(C_6F_5)_2]$  and employing two different  $\alpha$ -dicationic chelating ancillary ligands, both containing a PPh<sub>2</sub> moiety and a strong  $\pi$ -acceptor  $[P(Me_2Im)_2]^{+2}$  unit (Me<sub>2</sub>Im = 1,3-dimethylimidazolidine-2-ylidene) connected via *o*-phenylene or 2,2'-biphenylene linkers, respectively. Both complexes were calculated to have a low energy barrier (~23 kcal/mol) for reductive elimination due to the strong acceptor character of the ancillary ligands which enhances electron deficiency at the Pd center. However, they found these complexes unsuitable for catalysis as, after reductive elimination, the resulting Pd(0) complex inserted into one of the P–C bonds of the dicationic ligands to form Pd(II) phosphinidene complexes.

We recently reported the thermal<sup>13a</sup> and photocatalytic<sup>13b</sup> defluoroborylation of fluoroarenes using an NHC-nickel complex as catalyst (NHC = N-Heterocyclic Carbene) and B<sub>2</sub>pin<sub>2</sub> (pin = pinacolato) as the boron source. Subsequently, we focused on applications of the resulting Ar<sub>F</sub>–Bpin products in organic synthesis. Very recently, we reported optimized conditions for Suzuki-Miyaura cross-coupling of Ar<sub>F</sub>–Bpin with aryl–iodide / bromide as a coupling partner, using a combination of CuI and phenanthroline as the catalyst precursor,<sup>14</sup> and the Ni-catalyzed Suzuki-Miyaura crosscoupling of arylboronates with polyfluorinated arenes via C-F activation.<sup>13c</sup> Herein we expand the applications of Ar<sub>F</sub>–Bpin species to the homocoupling reaction using a palladium catalyst, as the reductive elimination from Pd(II)(2,6-C<sub>6</sub>F<sub>2+n</sub>H<sub>3-n</sub>)<sub>2</sub> complexes to generate symmetrical fluorinated biphenyls is still very challenging. Symmetrical polyfluorinated biphenyls have been receiving considerable attention as they have potential applications in organic semiconductors,<sup>15</sup> electrontransport materials,<sup>16</sup> crystal-engineering,<sup>17</sup> and supramolecular chemistry.<sup>18</sup> Fluorinated organic compounds, as well as some metal complexes with a fluorinated aryl ligand, are prospective antiproliferative agents against HT-29 (colon carcinoma) and MCF-7 (breast adenocarcinoma).<sup>9</sup>

Thus, we report a strategy to enhance the reductive elimination rate of  $Pd(II)(2,6-C_6F_{2+n}H_{3-n})_2$ complexes in the Pd-catalyzed homocoupling of  $Ar_F$ -Bpin compounds. Using acetonitrile as the reaction solvent, we also isolated the complexes cis-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (**3a**), cis-[Pd(MeCN)<sub>2</sub>(2,4,6-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>)<sub>2</sub>] (**3b**), and cis-[Pd(MeCN)<sub>2</sub>(2,6-C<sub>6</sub>F<sub>2</sub>H<sub>3</sub>)<sub>2</sub>] (**3e**) after double transmetalation, as these proved resistant to reductive elimination. However, the Pd-catalyzed homocoupling of 2,6-C<sub>6</sub>F<sub>2+n</sub>H<sub>3-n</sub>Bpin substrates proceeds smoothly if no ancillary ligand or strongly coordinating solvent is used. DFT computations were performed to gain additional insight into the reductive elimination step and to understand why the catalytic homocoupling reactions conducted in arene solvents is efficient, whereas it is difficult in the presence of ancillary ligand or coordinating solvents.

# **RESULTS AND DISCUSSION**

**Experimental studies.** We began by examining the homocoupling reaction of  $0.6 \text{ mmol of } C_6F_5Bpin$ catalyzed by 2 mol% of Pd(OAc)<sub>2</sub> in the presence of stoichiometric  $Ag_2O$ , which not only acts as an oxidizer for *in situ* formed Pd(0), but is also suggested to act as an accelerator for the transmetalation process.<sup>5b,19,20</sup> For example, Osakada et al. reported that trans-[Pd(PEt<sub>3</sub>)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)I] reacts with Ag<sub>2</sub>O in toluene/H<sub>2</sub>O to generate trans-[Pd(PEt<sub>3</sub>)<sub>2</sub>( $C_6F_5$ )(OH)], which undergoes facile transmetalation with the boronic acid 4-MeOC<sub>6</sub>H<sub>4</sub>B(OH)<sub>2</sub>.<sup>5b</sup> As it is well documented that employing strong Lewis basic ligands, such as mono- or bidentate phosphorus or nitrogen based ligands, stops the coupling reaction by formation of stable  $[PdL_2(C_6F_5)_2]$  complexes,<sup>3</sup> to facilitate the reductive elimination of  $C_6F_5-C_6F_5$ we planned to conduct the coupling reaction in weakly coordinating solvents without adding any ancillary ligands. It was anticipated that these solvents, upon coordination to the Pd center, would provide a less electron-rich environment at the metal center, thereby facilitating reductive elimination from the presumably four-coordinate cis-[Pd(solvent)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] complex or three-coordinate cis- $[Pd(solvent)(C_6F_5)_2]$  complex. It was previously proposed that acetonitrile can act as a labile ligand in cis-[Pd(MeCN)(PMe<sub>3</sub>)(R)<sub>2</sub>] (R = Me, Ph, vinyl).<sup>21</sup> This lability enables facile generation of the threecoordinate complex  $[Pd(PMe_3)(R)_2]$  and the ensuing reductive elimination of R<sub>2</sub>. Conducting the reaction in acetonitrile solvent, which was neither anhydrous nor dried or distilled, however, did not lead to homocoupling (Scheme 2). Using dry acetonitrile did not help. Likewise, no homocoupling product was formed with the arylboronates 2,4,6-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>Bpin (1b), 2,3,4,6-C<sub>6</sub>F<sub>4</sub>HBpin (1c), 2,3,5,6- $C_6F_4HBpin$  (1d), or 2,6- $C_6F_2H_3Bpin$  (1e) in this solvent (Scheme 2). However, with 2,3,4- $C_6F_3H_2Bpin$ 

(1f), which has only one *ortho*-fluorine substituent, a quantitative formation of the homocoupled product 2f was observed. From these data, it is clear that the reductive elimination is difficult only if the  $Ar_F$ -Bpin contains two *ortho*-fluorine substituents.<sup>4,5b,9,10</sup> This phenomena is in accordance with the theoretical research by Jones *et al.*<sup>8a</sup> and Perutz *et al.*<sup>8b,c</sup> who showed that the strength of the M–aryl bond strongly depends on the number of *ortho*-fluorine substituents on the aryl ring. Thus, it can be suggested that diaryl complexes containing two *ortho*-fluorines on each aryl ring have a high Pd-Ar bond energy and, in turn, a higher energy barrier for the reductive elimination step than those containing only one or no *ortho*-fluorine substituent.

Scheme 2. Pd-catalyzed homocoupling of ArF<sub>n</sub>-Bpin in MeCN.<sup>a</sup>



<sup>*a*</sup>General condition: 0.6 mmol of Ar<sub>F</sub>-Bpin (1), 2 mol% of Pd(OAc)<sub>2</sub>, 0.6 mmol of Ag<sub>2</sub>O, in 1.5 ml of MeCN, 5 h, at 75 °C, air. <sup>*b*</sup>No product was observed. <sup>*c*</sup>Isolated yield.

The reaction of 1.2 mmol of  $C_6F_5Bpin$  (1a), 2,4,6- $C_6F_3H_2Bpin$  (1b), or 2,6- $C_6F_2H_3Bpin$  (1e) with 0.4 mmol of Pd(OAc)<sub>2</sub> and 1.6 mmol of Ag<sub>2</sub>O in 4 mL of MeCN for 16 h at 60 °C stopped after the double transmetalation step (Scheme 3), and the resulting complexes *cis*-[Pd(MeCN)<sub>2</sub>( $C_6F_5$ )<sub>2</sub>] (3a), *cis*-[Pd(MeCN)<sub>2</sub>(2,4,6- $C_6F_3H_2$ )<sub>2</sub>] (3b), and *cis*-[Pd(MeCN)<sub>2</sub>(2,6- $C_6F_2H_3$ )<sub>2</sub>] (3e) were isolated in

good yields. All these products were characterized by NMR and IR spectroscopy, elemental analysis and single-crystal X-ray diffraction (Figure 1 and Supporting Information).

Scheme 3. Synthesis of *cis*-[Pd(MeCN)<sub>2</sub>(ArF<sub>n</sub>)<sub>2</sub>].<sup>*a*</sup>



<sup>*a*</sup>General conditions: 1.20 mmol of Ar<sub>F</sub>-Bpin, 0.40 mmol of Pd(OAc)<sub>2</sub>, 1.60 mmol of Ag<sub>2</sub>O, in 4 mL of MeCN, 16 h, 60 °C, in air. <sup>*b*</sup>Isolated yield.

Single crystals of *cis*-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (**3a**), *cis*-[Pd(MeCN)<sub>2</sub>(2,4,6-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>)<sub>2</sub>] (**3b**), and *cis*-[Pd(MeCN)<sub>2</sub>(2,6-C<sub>6</sub>F<sub>2</sub>H<sub>3</sub>)<sub>2</sub>] (**3e**) were grown by vapor diffusion of CD<sub>3</sub>CN/Et<sub>2</sub>O solutions placed in a larger vessel containing toluene (**3a**, **3e**) and by vapor diffusion of an Et<sub>2</sub>O solution with hexane (**3b**). The crystal structures, as shown in Figure 1, reveal that the complexes have *cis*-conformations, as reported for other complexes such as *cis*-[PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], (L = THF,<sup>22a</sup> CO,<sup>22a</sup> NH<sub>3</sub>,<sup>22b</sup> NH=CMe<sub>2</sub>,<sup>22b</sup> NH=C(OMe)Me,<sup>22c</sup> 7-azaindolyl<sup>22d</sup> and PPh<sub>3</sub><sup>3i</sup>).



**Figure 1.** Molecular structures of **3a** (left), **3b** (middle), and **3e** (right) determined by single-crystal X-ray diffraction at 100 or 103 K. Ellipsoids are drawn at the 50% probability level, and H atoms as well as the disordered diethyl ether solvent molecule are omitted for clarity. Only one of two symmetry independent molecules of **3b** is shown. Colors: red (palladium), green (fluorine), blue (nitrogen), white (carbon).

The isolation of complexes **3a**, **3b**, and **3e** shows that even a weakly donating ligand such as MeCN is sufficient to stabilize the  $[Pd(C_6F_5)_2]$ ,  $[Pd(2,4,6-C_6F_3H_2)_2]$ , and  $[Pd(2,6-C_6F_2H_3)_2]$ complexes, formed after double transmetalation, and thus to inhibit reductive elimination. Yamamoto et al.<sup>3g</sup> suggested that effective reductive elimination from [PdL<sub>n</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] depends on weak Pd- $C_{ipso}(C_6F_5)$  bonds and shorter  $C_{ipso}(C_6F_5)-C_{ipso}(C_6F_5)$  distances. Jones *et al.*<sup>8a</sup> and Perutz *et al.*<sup>8b,c</sup> reported that the maximum increase in M-aryl bond strength is achieved with two ortho-fluorine substituents, while the total number of fluorines only has a minor effect on the M-aryl bond strength. As shown in Table 1, the Pd-Cipso(Ar<sub>F</sub>) lengths, as well as Cipso(Ar<sub>F</sub>)-Cipso(Ar<sub>F</sub>) distances and  $C_{ipso}(Ar_F)$ -Pd- $C_{ipso}(Ar_F)$  angles are almost the same for cis-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (3a), cis- $[Pd(MeCN)_2(2,4,6-C_6F_3H_2)_2]$  (**3b**), and *cis*- $[Pd(MeCN)_2(2,6-C_6F_2H_3)_2]$  (**3e**).

Table 1. Selected bond lengths (Å) and angles (°) of 3a, 3b, and 3e.

	3a	3	3e	
		Molecule 1	Molecule 2	
$Pd-C_{ipso}(Ar_F)$	1.998(3)	1.988(2)	1.997(2)	1.996 (4)
		2.002(2)	1.997(2)	1.998 (4)
$C_{ipso}(Ar_F) \cdots C_{ipso}(Ar_F)$	2.774(5)	2.773(3)	2.755(3)	2.752 (5)
$C_{ipso}\!\!-\!\!Pd\!\!-\!\!C_{ipso}$	87.94(15)	88.06(9)	87.23(9)	87.09 (15)
∠ Ar–Ar	72.75(13)	98.77(8)	73.38(8)	86.76(11)

We then continued to screen conditions for the homocoupling of  $C_6F_5Bpin$  (1a) (Table 2). Intriguingly, shifting from coordinating solvents to non-coordinating ones<sup>23</sup> such as toluene, benzene, or *m*-xylene generated the homocoupling product  $C_6F_5$ - $C_6F_5$  (2a) in nearly quantitative yield (entry 1). The reaction is found to be slow in perfluorobenzene solvent, as it required 3 days to afford good yield (entry 2). It should be noted that the arene solvents used were neither anhydrous nor dried or distilled. In contrast to the outcomes obtained using arene solvents, no product was observed when coordinating solvents such as THF or NEt<sub>3</sub> were used (entry 3); presumably, stable  $[PdL_2(C_6F_5)_2]$  (L = THF, NEt<sub>3</sub>) complexes were formed. In fact, the stable cis-[Pd(THF)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>]<sup>22a</sup> and cis-[Pd(NH<sub>3</sub>)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>]<sup>22b</sup> complexes are well known. Using other coordinating solvents such as DMF or

DMSO also failed to afford homocoupling product. In contrast to  $Pd(OAc)_2$ , heterogenous Pd(0), namely Pd/C, did not catalyze the homocoupling reaction (entry 4), indicating that our catalytic process is not promoted by clusters, nanoparticles, etc. No homocoupling product was formed when using PdCl<sub>2</sub> instead of Pd(OAc)<sub>2</sub> (entry 5). This unsuccessful outcome is likely due to the poor solubility of PdCl<sub>2</sub> in toluene.

Espinet *et al.* reported that addition of 2 equivalents of  $PtBu_3$  to *cis*-[Pd(THF)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] in toluene enhances the reductive elimination of C<sub>6</sub>F<sub>5</sub>-C<sub>6</sub>F<sub>5</sub> under much milder conditions (Scheme 1).<sup>12</sup> The authors suggested that fast ligand substitution with the bulky, strongly  $\sigma$ -donating  $PtBu_3$  ligand leads to a three-coordinate Pd complex,<sup>24</sup> *cis*-[Pd(PtBu<sub>3</sub>)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], and enhances the elimination of C<sub>6</sub>F<sub>5</sub>-C<sub>6</sub>F<sub>5</sub>. Inspired by that, we added 4 mol% of  $PtBu_3$  as a ligand to the reaction mixture to examine for the possibility of achieving efficient catalytic reaction under ambient conditions but, unfortunately, it failed to generate any homocoupling product, even at a high temperature (Table 2, entry 6). We did not screen any other phosphine ligands, as many complexes of the form [Pd(PR<sub>3</sub>)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] are known and are stable with respect to reductive elimination.<sup>3,5b</sup>

<b>Table 2.</b> Reaction conditions screened	l for	Pd-cata	lyzed	homocoup	oling	of Ar <sub>F</sub> -B	pin.4
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F F Bpin -		Pd(OAc) <sub>2</sub> (2 mol%) Ag <sub>2</sub> O (0.6 mmol)				
		Solvent, 75 °C		5 O6 5		
<b>1a</b> (0.6 mmol)				2a		
Entry	S	Solvent	Time (h)	Yield $(\%)^b$		
1	Toluene, ber	zene, or <i>m</i> -xylene	5	> 94		
2	$C_6F_6$		5	36		
			24	54		
			72	75		
3	THF, NEt <sub>3</sub> , I	DMF, or DMSO	5	$0^c$		
4	Toluene		24	trace $d$		
5	Toluene		5	trace <sup>e</sup>		
6	Toluene + 4	mol% of PtBu <sub>3</sub>	24	$0^{c} (0)^{c,f}$		

<sup>*a*</sup>General conditions: 0.60 mmol of **1a**, 2 mol% of Pd(OAc)<sub>2</sub>, 0.60 mmol of Ag<sub>2</sub>O, in 1.5 mL of solvent, 5-72 h, 75 °C, in air. <sup>*b*</sup>Isolated yield. <sup>*c*</sup> Product was not observed. <sup>*d*</sup>Using Pd/C (0.5, 5 or 10 mol%) in place of Pd(OAc)<sub>2</sub>. <sup>*e*</sup>Using PdCl<sub>2</sub> (2 mol%) in place of Pd(OAc)<sub>2</sub>. <sup>*f*</sup>Under argon and using dried toluene.

We attempted to employ  $C_6F_5H$  instead of  $C_6F_5Bpin$  as a substrate in toluene under the above optimized conditions, but no homocoupling product was generated (Scheme 4A),<sup>25</sup> consistent with a process in which the C-Bpin moiety is important for transmetalation, and that C-H oxidative addition did not occur in toluene solvent. Interestingly, however, conducting the same reaction in MeCN solvent afforded a 74% isolated yield of complex **3a** (Scheme 4B), indicating that MeCN could function as a base and/or a sufficiently strong donor ligand on Pd to activate the C-H bond of  $C_6F_5H$ ,<sup>25d</sup> but MeCN solvent has to be avoided if the reductive elimination product **2a** is desired. Notably, no conversion was observed when employing 1,3,5-trifluorobenzene and 1,5difluorobenzene as substrates, even in MeCN solvent (Scheme 4B).

Using toluene as the solvent under the above optimized conditions, we expanded the scope to other fluorinated aryl-Bpin derivatives (Scheme 5). Compounds in which the C–Bpin bond is flanked by two C–F bonds (1a, 1b, 1c, 1d, 1e), only one C–F bond (1f, 1g) or no *ortho*-fluorines (1h), all proved to be suitable substrates, and the respective homocoupled products 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h were formed in excellent yields.

Scheme 4. Attempted homocoupling reaction using C<sub>6</sub>F<sub>5</sub>H, 1,3,5-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>, and 1,5-C<sub>6</sub>F<sub>2</sub>H<sub>3</sub> substrates.



<sup>*a*</sup>Condition: C<sub>6</sub>F<sub>5</sub>H (0.6 mmol), Pd(OAc)<sub>2</sub> (2 mol%), Ag<sub>2</sub>O (0.6 mmol), toluene (1.5 ml), 75 °C, 5 h, in air. <sup>*b*</sup>Conditions: ArF<sub>n</sub> (4 mmol), Pd(OAc)<sub>2</sub> (0.4 mmol), Ag<sub>2</sub>O (1.6 mmol), MeCN (4 ml), 60 °C, 16 h, in air.



<sup>a</sup>General conditions: Ar<sub>F</sub>-Bpin (0.6 mmol), Pd(OAc)<sub>2</sub> (2 mol%), Ag<sub>2</sub>O (0.6 mmol), toluene (1.5 mL), 75 °C,
5 h, in air. <sup>b</sup>Isolated yield.

Crystal and molecular structures of the fluorinated biaryl products: Intermolecular  $\pi \cdots \pi$  stacking interactions. Crystal structures of the products 2,2',3,3',5,5',6,6'-octafluorobiphenyl (2d) and 2,2',3,3',4,4'-hexafluorobiphenyl (2f) were obtained via single-crystal X-ray diffraction. The molecular geometries of these compounds in their crystal structures are shown in Figure 2. The central C–C bonds are equal within one standard deviation and are in the range 1.485(2) – 1.487(4) Å (Table 3) which is typical of biphenyl compounds.<sup>26</sup> The twist between the aryl moieties of the biaryl compounds is slightly stronger in 2d (58.06(4)°) than in 2f (47.02(6)°) (Table 3). This difference is likely due to the larger steric demand of fluorine in close vicinity to the central C–C bond joining the rings and, hence, to the stronger repulsion between the fluorine atoms of both aryl units in 2d. A similar twist angle to that of 2f was also reported for 2,3,4-trifluorobiphenyl (49.76(7)°).<sup>14</sup>



**Figure 2.** Solid-state molecular structures of **2d** (left) and **2f** (right) determined by single-crystal X-ray diffraction at 100 K. Ellipsoids are drawn at the 50% probability level, and H atoms are omitted for clarity. Compound **2f** shows a two-fold rotational symmetry. Colors: white (carbon), green (fluorine).

	2d	2f
conjunction bond CAryl-CAryl	1.4852(16)	1.487(4)
∠ Aryl-Aryl	58.06(4)	47.02(6)
centroid-centroid distance	-	3.6980(1)
interplanar separation	-	3.3911(16)
offset shift <sup>a</sup>	-	1.475(4)

**Table 3.** Selected bond lengths (Å) and angles (°) of 2d and 2f, and  $\pi \cdots \pi$  stacking distances in 2f.

<sup>*a*</sup>The offset shift, also called inter-centroid shift, is the distance within a plane of an aryl ring between the centroid of the respective aryl ring and the intersection point with the normal to the plane through the centroid of the other aryl ring.

Particularly interesting in the crystal structure analysis are the intermolecular interactions and, hence, molecular packing in these compounds. In compound **2d** there are no  $\pi$ - $\pi$  stacking interactions present. A weak C–H…F interaction with an angle of 124.62(8)° and a few weak F…F interactions with distances of 2.7078(12)–2.9169(15) Å are observed between the molecules (Table S2 in the Supporting Information). However, in compound **2f**, the biaryls form columns of offset face-to-face  $\pi$ -stacked 2,3,4-trifluoro phenyl rings along the *c* axis. The interplanar separation between the trifluorophenyl rings is typical for  $\pi$ - $\pi$  stacking interactions (3.3911(16) Å, Table 3). Due to the large twist angle of ca. 47° of the biaryl, the columnar stacks are cross-like (Figure 3). Similar cross-like columnar stacks are observed in 2,3,4,5,6-pentafluorobiphenyl,<sup>27a</sup> 1,2,4,5-tetrafluoro-3-phenyl-6(trifluoromethyl)benzene,<sup>27a</sup> 4'-bromo-2,3,5,6-tetrafluorobiphenyl-4-carbonitrile,<sup>27a</sup> and 2-(perfluorophenyl)naphthalene<sup>14</sup> which show biphenyl twist angles of 52, 50, 41, and 51°, respectively.



Weak intermolecular C–H…F and F…F interactions are formed between the stacks (Table S2 in the Supporting Information).



**Figure 3.** Crystal structure of **2f** projected along the *c* axis (top), which is the stacking direction of the molecules, and the *a* axis (bottom), at 100 K. Trifluorophenyl rings are  $\pi$ -stacked along the *c* axis. The intramolecular angle between the aryl rings of the biaryl is 47° leading to the formation of cross-like stacks (bottom). Only a section of the crystal structure, i.e., one fourth along the *a* direction, is plotted in the bottom projection, while four unit cells are shown along the *c* axis. Ellipsoids are drawn at the 50% probability level, and H atoms are omitted for clarity. Colors: white (carbon), green (fluorine).

**Computational studies.** The observation that stable highly fluorinated diaryl palladium(II) complex ligated with two acetonitriles, cis-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (**3a**), can be isolated from our attempted catalytic homocoupling reactions conducted in acetonitrile suggests that the transmetalation process is facile under the reaction conditions employed. It is also apparent that the transmetalation step is facile for the reactions performed in other solvents, including THF, benzene, toluene, *m*-xylene and probably perfluorobenzene. Thus, it can be proposed that the rate determining step in these homocoupling reactions is reductive elimination. To understand why the catalytic homocoupling reactions conducted in acetonitrile and THF failed, while they are successful in arene solvents, computations on the reductive elimination step were performed using DFT at the B3LYP-

D3/Def2TZVP/6-311+g(2d,p)/IEFPCM // B3LYP-D3/SDD/6-31g\*\*/IEFPCM level (see Supporting Information for details).

Brief overview of previous theoretical studies on reductive elimination from *cis*-[PdL<sub>2</sub>RR']. Several theoretical studies on C-H, C-C, C-E, and C-X reductive elimination from palladium complexes of type cis-[PdL<sub>2</sub>R<sub>2</sub>] have been reported. However, in comparison to the oxidative addition step, reductive elimination has been less well studied theoretically.<sup>28</sup> For a long time, the reductive elimination step was generally assumed to be fast and irreversible. However, recent experimental studies have shown that there are systems in which reductive elimination is a slow step for the formation of C-C bonds.<sup>29</sup> Based on previous theoretical studies, reductive elimination from *cis*- $[PdL_2R_2]$  is generally accepted to be a concerted step occurring from a *cis*-complex. The earliest detailed theoretical study on reductive elimination from d<sup>8</sup>-metal complexes of group 10 metals was the 1981 report by Tatsumi et al.<sup>30</sup> In this study, the authors employed extended Hückel calculations with a weighted *Hij* approximation and analyzed how switching the transition metal within the same group, as well as the ligands on the square planar complexes influences the activation barrier for the reductive elimination of two *cis*-positioned alkyl groups. This study disclosed that, in comparison to Pd(II) and Pt(II) complexes, Ni(II) complexes can readily facilitate the reductive elimination of ethane from two *cis*-positioned methyl ligands. Moreover, this study also suggested that, upon dissociation of one of the neutral ligands from cis-[ML<sub>2</sub>R<sub>2</sub>] complexes, the resulting three-coordinate complexes (*cis*-[MLR<sub>2</sub>]) can adopt either a T- or Y-shape geometry. Complexes with a T-shape geometry, that have the two eliminating groups positioned *cis* to each other, tend to undergo reductive elimination readily, whereas complexes with a Y-shape geometry tend to facilitate the *cis/trans* isomerization of the two alkyl groups.

Goddard *et al.* have explored theoretically, using the Hartree-Fock and generalized valence bond approximations, the factors which facilitate the reductive coupling of H–H, C–H and C–C bonds to produce molecular hydrogen and alkanes from the four-coordinate d<sup>8</sup>-complexes *cis*-[M(PH<sub>3</sub>)<sub>2</sub>RR'] (M = Pd, Pt; R, R' = H, Me), and reported that the reductive elimination barrier increases in the order H-H < C–H < C–C.<sup>31</sup> For this trend, the authors noted that the faster reductive elimination of H<sub>2</sub>

results from the better orbital overlap between the two eliminating hydride ligands, whereas the extent of such overlap is reduced as we move towards more carbon-based eliminating ligands for which the orbitals are more directed. For the C-C reductive elimination, Espinet et al. conducted a combined theoretical and experimental study on C<sub>sp3</sub>-C<sub>sp3</sub> and C<sub>sp2</sub>-C<sub>sp2</sub> reductive elimination from cis-[Pd(PMe<sub>3</sub>)<sub>2</sub>R<sub>2</sub>], and *cis*-[Pd(PMe<sub>3</sub>)LR<sub>2</sub>] complexes possibly formed *in situ* from addition of coupling promoters (L = acetonitrile, ethene, maleic anhydride) to cis-[Pd(PMe<sub>3</sub>)<sub>2</sub>R<sub>2</sub>].<sup>21</sup> Their computational study at the B3LYP/SDD/6-31g\* level of theory predicted a reductive elimination barrier of ~29 kcal/mol for the C<sub>sp3</sub>-C<sub>sp3</sub> coupling from *cis*-[Pd(PMe<sub>3</sub>)<sub>2</sub>(Me)<sub>2</sub>], and a barrier of ~12 kcal/mol for C<sub>sp2</sub>- $C_{sp2}$  coupling from complexes of the type *cis*-[Pd(PMe<sub>3</sub>)<sub>2</sub>R<sub>2</sub>] (R = vinyl and Ph). Morukuma *et al.* carried out a similar theoretical study, using the ONIOM(B3LYP/SDD/6-311g\*:B3LYP/LANL2DZ) level of theory, on the reductive elimination from Pd(II) and Pt(II) complexes by employing the simplest phosphine ligand PH<sub>3</sub> as a model.<sup>24b</sup> Their computations predicted a lower barrier for the model complexes of the type cis-[Pd(PH<sub>3</sub>)<sub>2</sub>R<sub>2</sub>] (R = Me, vinyl, Ph, ethynyl) compared to their PMe<sub>3</sub> analogues. For example, the reductive elimination barrier for C<sub>sp3</sub>-C<sub>sp3</sub> coupling was reduced from ~29 kcal/mol to ~24 kcal/mol upon switching the phosphine ligand from PMe<sub>3</sub> to PH<sub>3</sub>. Likewise, for the vinyl case, the barrier was reduced from 12 kcal/mol to 6 kcal/mol when PMe<sub>3</sub> is replaced with PH<sub>3</sub>. However, for the bis-phenyl complex, the reductive elimination barrier was predicted to be similar in both cases. While the reductive elimination barrier for  $C_{sp}$ - $C_{sp}$  coupling from the PMe<sub>3</sub> complex was not computed, it was calculated for the PH3 complex cis-[Pd(PH3)2(CCH)2] which was found to have a barrier of ~11 kcal/mol, i.e., in between the barriers of its vinyl and methyl analogues, with the vinyl complex having the lower barrier.

Ariafard and Yates reported details of both electronic and steric effects of phosphine ligands on the reductive elimination of ethane and butadiene from cis-[Pd(PR<sub>3</sub>)<sub>2</sub>R<sub>2</sub>] (R = Me, vinyl) at the B3LYP/LANL2DZ/6-31g\* level of theory.<sup>24a</sup> The authors concluded that both factors play a role in the reductive elimination process for the parent four-coordinate complex, whereas only the electronics dominated in the three-coordinate complex cis-[Pd(PR<sub>3</sub>)R<sub>2</sub>], formed from the parent complex via dissociation of a PR<sub>3</sub> ligand. Notably, steric factors in the starting four-coordinate complex cis-

 $[Pd(PR_3)_2R_2]$  destabilizes it, while both factors stabilized the reductive elimination transition state. These factors led to a reduced reductive elimination barrier for this step. However, this reduced barrier is still high relative to that of the respective three-coordinate complex. Overall, from all these computational studies, the reductive elimination barrier for C-C coupling from the four- and threecoordinate Pd(II) complexes generally increases in the order  $C_{sp}-C_{sp} < C_{sp2}-C_{sp3} < C_{sp3}-C_{sp3}$ . In 2010, Korenaga et al. reported a combined experimental and theoretical study (theory level: B3LYP/LANL2DZ/6-31g\*) of the electronic and steric effects of various diphosphine ligands on reductive elimination of biphenyl from the Pt(II) complex cis-[Pt(diphosphine)(Ph)<sub>2</sub>].<sup>32</sup> The authors suggested that the electronic effects of diphosphine ligands contribute mainly to the reductive elimination rates. In particular, electron-poor diphosphine ligands that have the ability to act as a weak  $\sigma$ -donor significantly reduced the reductive elimination barrier in comparison to the ones which are strongly  $\sigma$  donating.<sup>32</sup> It was reasoned that electron-poor diphosphine ligands decrease the dorbital energy gap between the important high-lying molecular orbital of the starting four-coordinate complex and its reductive elimination transition state, and thereby reduce the reductive elimination barrier. Thus far, much theoretical focus was placed on the reductive elimination of different C-C single bonds and, to the best of our knowledge, there was only one report on a computational study of C<sub>sp2</sub>-C<sub>sp2</sub> reductive elimination from [PdL<sub>2</sub>(Ar)<sub>2</sub>] complexes containing fluorinated aryl ligands.<sup>3h</sup> Alcarazo et al. reported a combined experimental and computational study of the reductive elimination from symmetrical and dicationic unsymmetrical diphosphine ligand-containing Pd(II) complexes of type *cis*-[Pd(diphosphine)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>]. Their computations at the BP86-D3/def2-SVP level of theory revealed that the dicationic unsymmetrical diphosphine ligand makes the coupling process not only exergonic but also, remarkably, reduces the reductive elimination barrier to ~23 kcal/mol, whereas employing a symmetrical ligand makes the process highly endergonic with a barrier of  $\sim 32$ kcal/mol. By virtue of its strong  $\pi$ -accepting character, the cationic phosphine component of the unsymmetrical diphosphine ligand was reasoned to be responsible for the reduced reductive elimination barrier in the former case, as the cationic phosphine unit readily accepts the electron density that is accumulated on the metal during the transition state for the reductive elimination process.

Computational Results and Discussion. It was previously demonstrated that the Pd-catalyzed Suzuki-Miyaura cross-coupling of  $C_6F_5$ -boronates with aryl iodides or bromides requires a stoichiometric amount of silver oxide (Ag<sub>2</sub>O) to accelerate the transmetalation between  $C_6F_5$ boronates and Pd(II) complexes. Ag<sub>2</sub>O has not been considered to play a role in the reductive elimination from a diaryl palladium complex.<sup>5b,20</sup> Other previous studies have indicated that the acceleration of transmetalation with  $Ag_2O$  in the presence of  $H_2O$  led to the generation of an hydroxy complex that shows a higher reactivity for transmetalation with arylboronates.<sup>5b,20c</sup> In our case, the formation of a stoichiometric amount of the stable diaryl palladium(II) intermediate cis- $[Pd(MeCN)_2(C_6F_5)_2]$  (3a), *cis*- $[Pd(MeCN)_2(2,4,6-C_6F_3H_2)_2]$  (3b), and *cis*- $[Pd(MeCN)_2(2,6-C_6F_2H_3)_2]$ (3e) from the homocoupling reactions conducted in acetonitrile solvent with excess  $Ag_2O$  present implies that  $Ag_2O$  is ineffective in accelerating the reductive elimination process. Moreover, treatment of 3e in the non-polar solvent toluene without addition of Ag<sub>2</sub>O led to decomposition and gave the reductive elimination product 2e quantitatively, implying again that Ag<sub>2</sub>O does not accelerate reductive elimination. Hence, our computational emphasis was placed exclusively on the reductive elimination step without the engagement of Ag<sub>2</sub>O. As the reaction conducted in acetonitrile led to intermediate 3a, two possible mechanistic routes from this intermediate, as shown in Figure 4, were conceived for the coupling step. The first route involves a concerted reductive elimination pathway whereby reductive elimination takes place directly from complex 3a, and the second route, a dissociative pathway, involves an initial dissociation of an MeCN ligand,<sup>19</sup> leading to the threecoordinate Pd(II) complex cis-[Pd(MeCN)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], followed by reductive elimination. Computations at the B3LYP-D3/TZVP level of theory show that this is a slightly endergonic reaction and the barrier for reductive elimination directly from cis-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (3a) is 34.3 kcal/mol (pathway A, Figure 4). The second route (pathway B, Figure 4) did not bring down the overall reductive elimination barrier significantly with respect to that of pathway A, although the barrier of the actual reductive elimination step itself via this route was reduced by 8.9 kcal/mol. As this coupling reaction is already slightly endergonic and possess a high barrier achieving this reaction catalytically is unlikely. Like acetonitrile, THF can also form the bis(solvent) complex cis-[Pd(THF)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (7).



**Figure 4.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C–C reductive elimination step from the bis-perfluoroaryl complex ligated with acetonitrile. Gibbs free energy values (kcal/mol) relative to reactant (**3a**) are given in parentheses.



**Figure 5.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C–C reductive elimination step from the bis-perfluoroaryl complex ligated with THF. Gibbs free energy values (kcal/mol) relative to reactant (7) are given in parentheses.

While the THF complex 7 was not isolated or observed in our reactions, it is a known compound which was structurally characterized by X-ray crystallography.<sup>22a</sup> Therefore, for reactions conducted in THF, the involvement of two routes resembling that of acetonitrile can be envisioned. For the first route (Pathway A, Figure 5), computations predict a high barrier comparable to that of the acetonitrile complex *cis*-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (**3a**). Even via the second route, i.e., the dissociative pathway, no reduction in the overall barrier was obtained (pathway B, Figure 5). Furthermore, this homocoupling reaction is highly endergonic. Overall, such catalytic homocoupling reactions attempted in THF will likely not be rewarding. While this was the exact outcome we obtained from the experiments conducted in THF, the recent demonstration by Espinet *et al.*<sup>12</sup> of successful reductive coupling of

perfluorobiphenyl using the synthesized THF complex *cis*-[Pd(THF)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (7) in toluene suggests that either a THF ligand dissociates or both THF ligands were displaced by a toluene solvent prior to the reductive elimination step. Only under one of these conditions could their reported experimental barrier of 23.1 kcal/mol be obtained. Though not experimentally explored in the current work, we have computationally explored the possibilities of reductive elimination from the bis(perfluorophenyl)palladium complexes containing two other simple ligands. namely dimethylsulfide and trimethylphosphine. Two mechanistic pathways, as discussed above for complex cis-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (**3a**), are also possible with these ligands. Calculations show that, with these two ligands, the reductive elimination barriers remain high for the first route (pathway A, Figures 6 and 7), and the overall barrier is even higher for the second route (pathway B, Figures 6 and 7). Overall, our computations on reductive elimination from fluorinated bis-phenyl square planar complexes of the type cis-[PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] suggest that the barrier for reductive elimination from the four-coordinate complex is too high to overcome under the reaction conditions we employed, and the T-shaped tricoordinate complexes of type  $[PdL(C_6F_5)_2]$  that result from the dissociation of L in *cis*- $[PdL_2(C_6F_5)_2]$ , while possessing a lower barrier for the actual reductive elimination step, still place the overall reductive elimination barrier at similar or higher energies than those of cis-[PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>].



**Figure 6.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C-C reductive elimination step from the bis-perfluoroaryl complex ligated with dimethylsulfide. Gibbs free energy values (kcal/mol) relative to reactant (**12**) are given in parentheses.



**Figure 7.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C-C reductive elimination step from the bis-perfluoroaryl complex ligated with PMe<sub>3</sub>. Gibbs free energy values (kcal/mol) relative to reactant (16) are given in parentheses.

To understand the feasibility of the catalytic reactions in aromatic solvents, computations were performed on two mechanistic pathways for reductive elimination: (i) with an aromatic solvent coordinated to the metal; and (ii) without any arene coordination to the metal. Benzene, toluene, *m*xylene, and perfluorobenzene were explored as solvents. For the metal complexed with an aromatic solvent, a slightly distorted  $\eta^6$ -interaction was calculated for the ground state structure of  $[Pd(\eta^6$  $arene)(C_6F_5)_2]$ . Ring slippage of the arene ligand along the reaction coordinate was calculated to occur and the hapticity change may best be described as going from  $\eta^6$  in the reactant to  $\eta^n$  ( $n \le 3$ ) in the transition state and the products. The optimized structures of the benzene complex  $[Pd(\eta^6 C_6H_6)(C_6F_5)_2]$  **20**, the primary elimination product **21** and of the transition state **TS(20-21)** (see also Figure 9) are shown in Figure 8.



**Figure 8.** Side-view (a) and view along the arene-Pd vector (b) of the DFT-optimized structures (B3LYP-D3/TZVP) of the benzene complexes  $[Pd(\eta^6-C_6H_6)(C_6F_5)_2]$  **20**, the primary elimination product **21** and the transition state **TS(20-21)**. Calculated Pd-C<sub>arene</sub> distances [Å]: **20**: 2.61735, 2.61795, 2.64026, 2.64086, 2.66559, 2.66676, **TS(20-21)**: 2.27466, 2.60792, 2.60934, 3.20505, 3.20613, 3.47771, **21**: 2.23648, 2.56489, 2.63107, 3.20371, 3.25464, 3.51379.

For  $[Pd(\eta^n-arene)(C_6F_5)_2]$  complexes **20**, **25**, **30** and **35** the overall reductive elimination process in all of the aromatic solvents is exergonic. In benzene, a reductive elimination barrier of only 20.4 kcal/mol ( $\Delta G^{\ddagger}$ ) was found for the first route (pathway A, Figure 9). This overall barrier, in comparison with that of the two routes for complexes that involve MeCN or THF solvent, is exceptionally low and can be readily overcome under the reaction conditions employed experimentally. The examination of a second route for reductive elimination led only to the observation of an elevated overall barrier of 29.8 kcal/mol (pathway B, Figure 9). Thus, due to the disparity in the barriers, it can be suggested that reductive elimination via the first route is predominant for this reductive elimination process. The computed results for reductive elimination of the two mechanistic routes involving the solvents toluene, *m*-xylene, and perfluorobenzene are displayed in Figures 10, 11, and 12, respectively. The computed free energy profiles in toluene



**Figure 9.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C-C reductive elimination step from the bis-perfluoroaryl complex ligated with benzene. Gibbs free energy values (kcal/mol) relative to reactant (20) are given in parentheses.

and *m*-xylene follows a similar trend to that in benzene. However, unlike in benzene, toluene and *m*xylene, in perfluorobenzene the dissociation of the perfluorobenzene from the postulated reactant 35 was found to be exergonic. Therefore, the overall barriers for both mechanistic routes which were found to be similar to each other come from the dissociated  $Pd(C_6F_5)_2$  complex 38. As a result, both pathways might be possible. Despite the lowest reductive elimination barrier predicted in this solvent, catalytic experiments provided lower conversions in comparison with the outcomes of catalytic experiments carried out in other aromatic solvents in the same reaction times (Table 2, entry 2). Prolonging the reaction time did improve the desired outcome of this reaction and afforded the product in a good yield (75%). One reason for such a slow conversion may be the deactivation of the catalyst, possibly via oxidative addition of a C-F bond of the coordinated perfluorobenzene solvent after the reductive elimination step, or the poor ability of the oxidizing reagent Ag<sub>2</sub>O to oxidize the electron-poor Pd(0) complex 36 that has formed after the reductive elimination step. The computed barrier for a C-F oxidative addition process was found to be only 24.8 kcal/mol (TS(36-40), Figure 12), which is accessible under our reaction conditions. However, treating the cis-[Pd(MeCN)<sub>2</sub>(2,6- $C_6F_2H_3)_2$  complex (3e) in toluene with 3 equiv of perfluorobenzene at 75 °C for a day did not show any indication of C-F oxidative addition to Pd(0) even though we obtained the coupled product 2e in >99% yield (see Supporting Information).



**Figure 10.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C-C reductive elimination step from the bis-perfluoroaryl complex ligated with toluene. Gibbs free energy values (kcal/mol) relative to reactant (**25**) are given in parentheses.



Figure 11. Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C-C reductive elimination step from the bis-perfluoroaryl complex ligated with *m*-xylene. Gibbs free energies (kcal/mol) relative to reactant (30) are given in parentheses.



**Figure 12.** Computed mechanistic pathways (DFT, B3LYP-D3/TZVP) for the C-C reductive elimination step from the bis-perfluoroaryl complex ligated with perfluorobenzene and a possible mode of deactivation of the catalyst. Gibbs free energy values (kcal/mol) relative to reactant (**35**) are given in parentheses.

As the reductive elimination process generates a lone pair on the transition metal, the level of stabilization of this lone pair  $(d_x^2,v^2)$  was examined by analyzing the interactions between the ligands  $L_2$  and  $\eta^n$ -Ar and the bent ( $C_{2\nu}$ ) fragment [Pd( $C_6F_5$ )<sub>2</sub>] of cis-[PdL<sub>2</sub>( $C_6F_5$ )<sub>2</sub>] (L = MeCN, THF, SMe<sub>2</sub>, PMe<sub>3</sub>) and  $[Pd(\eta^6-Ar)(C_6F_5)_2]$  (Ar = C<sub>6</sub>H<sub>6</sub>, C<sub>7</sub>H<sub>8</sub>, C<sub>8</sub>H<sub>10</sub>, C<sub>6</sub>F<sub>6</sub>) and their corresponding reductive elimination transition states. Thus, EDA-NOCV calculations,<sup>33</sup> performed at the B3LYP-D3/TZVP level of theory, offer detailed information on the interactions in terms of Pauli repulsion ( $\Delta E_{Pauli}$ ), attractive electrostatic interaction ( $\Delta E_{elstat}$ ) and orbital interaction ( $\Delta E_{orb}$ ) and also the attractive dispersion interaction ( $\Delta E_{disp}$ ) (Tables S3 and S4 in the Supporting Information). More explanations of these terms are provided in the EDA-NOCV analysis section in the Supporting Information. Table 4 summarizes the results of our calculations. The contribution to the overall barrier by distortion energy ( $\Delta\Delta E_{dist}$ ), which is the difference in energy penalty linked with the distortion of the interacting fragments from their equilibrium geometries to the frozen geometries of the reactant and transition state, was found to be similar in all cases with calculated  $\Delta\Delta E_{dist}$  values between +17.5 and +20.7 kcal/mol (Table 4, column a). Therefore, the differences observed for the barriers of the reductive elimination step for different ligands can be explained by contributions from the intrinsic interaction energies ( $\Delta E_{int} = \Delta E_{Pauli} + \Delta E_{elstat} + \Delta E_{orb} + \Delta E_{disp}$ ). The interaction energy  $\Delta E_{int}$  (Table 4, column b) of the reactants decreases in the order  $[Pd(PMe_3)_2(C_6F_5)_2]$  16 (-102.0 kcal/mol) >  $[Pd(SMe_2)_2(C_6F_5)_2]$  12  $(-70.8 \text{ kcal/mol}) > [Pd(THF)_2(C_6F_5)_2]$  7  $(-58.1 \text{ kcal/mol}) > [Pd(MeCN)_2(C_6F_5)_2]$  3a  $(-55.3 \text{ kcal/mol}) > (-70.8 \text{ kc$  $[Pd(\eta^{n}-C_{8}H_{10})(C_{6}F_{5})_{2}]$  **30** (-32.6 kcal/mol)  $\approx [Pd(\eta^{n}-C_{7}H_{8})(C_{6}F_{5})_{2}]$  **25** (-30.3 kcal/mol)  $\approx [Pd(\eta^{n}-C_{7}H_{8})(C_{6}F_{5})_{2}]$  $C_6H_6)(C_6F_5)_2$  20 (-27.4 kcal/mol) > [Pd( $\eta^n$ - $C_6F_6)(C_6F_5)_2$ ] 35 (-12.2 kcal/mol), which reflects the different behavior of the ligands.

 $\Delta E_{int}$  was reduced significantly for *cis*-[PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] when moving from the reactant to the reductive elimination transition state as indicated by the differences  $\Delta \Delta E_{int}$ . The interaction energy term between the ligands L<sub>2</sub> and [Pd(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] decreases for L = MeCN (**3a**,  $\Delta \Delta E_{int}$ = +19.9 kcal/mol), THF (**7**,  $\Delta \Delta E_{int}$ = +21.3 kcal/mol)), SMe<sub>2</sub> (**12**,  $\Delta \Delta E_{int}$ = +18.7 kcal/mol)) and PMe<sub>3</sub> (**16**,  $\Delta \Delta E_{int}$ = +25.0 kcal/mol) (Table 4, column b), whereas  $\Delta \Delta E_{int}$  remains almost constant for [Pd( $\eta^{n}$ -Ar)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (+1.2 to +4.3 kcal/mol) and even increases for [Pd( $\eta^{n}$ -C<sub>6</sub>F<sub>6</sub>)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (-4.7 kcal/mol). A closer inspection of

the sum of the electrostatic contributions  $\Delta\Delta E_{Pauli}$  and  $\Delta\Delta E_{elstat}$  reveals that it varies little, and remains almost constant going from the ground state to the transition state. The sum of  $\Delta\Delta E_{Pauli}$  and  $\Delta\Delta E_{elstat}$  is +3.2 kcal/mol for [Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], +4.8 kcal/mol for [Pd(THF)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], +1.5 kcal/mol for

**Table 4.** Results of EDA-NOCV analysis (B3LYP-D3/TZVP level of theory) on the interaction between the ligands  $L_2$  and  $\eta^n$ -Ar and the bent fragment ( $C_{2v}$ ) [Pd( $C_6F_5$ )<sub>2</sub>] of various reactants [Pd  $L_2(C_6F_5)_2$ ] (L = MeCN, THF, SMe<sub>2</sub>, PMe<sub>3</sub>) and [Pd( $\eta^n$ -Ar)( $C_6F_5$ )<sub>2</sub>] (Ar =  $C_6H_6$ ,  $C_7H_8$ ,  $C_8H_{10}$ ,  $C_6F_6$ ) and their corresponding transition states of the reductive elimination of perfluorobiphenyl from these complexes. Energies are given in kcal/mol.

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
L/Ar	$\Delta E_{\rm dist}$	$\Delta E_{\rm int}$	$\Delta E_{\text{Pauli}}$	$\Delta E_{\rm elstat}$	$\Delta E_{\rm orb}$	$\Delta E_{\sigma}$	$\Delta E_{\pi}$	$\Delta E_{\rm orb(rest)}$	$\Delta E_{\rm disp}$
MeCN (3a)	1.2	-55.3	130.6	-117.1	-60.6	-41.7	-8.6	-10.3	-8.2
TS(3a-4)	17.5	-35.4	106.5	-89.8	-45.1	-21.1	-14.2	-9.9	-7.0
TS(3a-4)-3a									
$(\Delta \Delta E)$	16.3	19.9	-24.1	27.3	15.5	20.6	-5.6	0.4	1.2
THF (7)	1.8	-58.1	102.5	-95.6	-44.2	-29.1	_a	-15.3	-20.8
TS(7-8)	17.9	-36.8	80.0	-68.3	-27.8	-18.1	a	-9.7	-20.7
TS(7-8)-7									
$(\Delta \Delta E)$	16.1	21.3	-22.5	27.3	16.4	11.0	_	5.6	0.1
$SMe_2$ (12)	2.7	-70.8	162.7	-141.2	-70.6	-47.4	-3.9	-19.3	-21.7
TS(12-13)	17.8	-52.1	163.9	-141.0	-54.5	-37.7	-4.0	-12.8	-20.6
TS(12-13)-12	15.1	10.7	1.0	0.2	16.1	0.7	0.1	<i>(</i> <b>-</b>	1.1
$\frac{(\Delta \Delta E)}{(\Delta \Delta E)}$	15.1	18./	1.2	0.3	16.1	9./	-0.1	6.5	1.1
$PMe_3$ (16)	5.6	-102.0	280.0	-250.1	-104.7	-79.2	-10.5	-15.0	-27.2
TS(16-17)	18.5	-77.0	281.1	-252.6	-81.4	-57.6	-11.9	-11.9	-24.1
TS(16-17)-16	12.0	25.0	1 1	25	<u></u>	21.6	1.4	2.1	2.1
$\frac{(\Delta \Delta E)}{C \Pi (20)}$	12.9	23.0	1.1 64.5	-2.3	25.2	21.0	-1.4	0.2	3.1 11.2
$C_6 \Pi_6 (20)$	1.0	-27.4	04.3	-43.5	-55.0	-22.8	-3.0	-9.2	-11.5
TS(20-21)	19.2	-26.2	66.8	-53.1	-31.3	-14.2	-12.4	-4.7	-8.6
TS(20-21)-20	17.6	1.2	23	-7.6	37	8.6	-9.4	4.5	27
<u>(ААЕ)</u> С.Н. (25)	1 8	-30.3	67.8	-48.5	-36.6	22.4	2.2	-10.0	
C/118 (25)	10.2	-50.5	68.0	-40.5	-30.0	-25.4	-5.2	-10.0	0.2
TS(25-20) TS(25-26)-25	19.2	-27.3	08.0	-54.0	-51.0	-14.4	-12.5	-4.0	-9.2
$(\Delta\Delta E)$	17.4	2.8	0.2	-6.0	4.8	9.0	-9.3	5.2	3.8
C <sub>8</sub> H <sub>10</sub> ( <b>30</b> )	1.9	-32.6	69.1	-50.5	-37.6	-20.8	-3.3	-13.5	-13.6
TS(30-31)	19.1	-28.4	68.3	-55.2	-30.7	-14.1	-11.5	-5.0	-10.7
TS(30-31)-30 (ΔΔΕ)	17.2	4.3	-0.8	-4.7	6.9	6.7	-8.2	8.5	2.9
C <sub>6</sub> F <sub>6</sub> ( <b>35</b> )	1.3	-12.2	53.6	-25.4	-28.9	-18.4	-2.1	-8.4	-11.6
TS(35-36)	20.7	-16.9	68.9	-41.5	-30.1	-9.7	-15.5	-4.8	-14.2
TS(35-36)-35 (ΔΔΕ)	19.4	-4.7	15.2	-16.2	-1.1	8.7	-13.4	3.6	-2.6

<sup>*a*</sup> No  $\pi$  back-donation interaction was found. Details about deriving different orbital interaction components  $(\Delta E_{\sigma}, \Delta E_{\pi} \text{ and } \Delta E_{\text{orb(rest)}})$  from the EDA-NOCV analysis are provided in the Supporting Information.

[Pd(SMe<sub>2</sub>)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], -1,4 kcal/mol for [Pd(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>(PMe<sub>3</sub>)<sub>2</sub>], -5.3 kcal/mol for [Pd( $\eta^{n}$ -C<sub>6</sub>H<sub>6</sub>)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], -5.8 kcal/mol for [Pd( $\eta^{n}$ -C<sub>7</sub>H<sub>8</sub>)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], -5.5 kcal/mol for [Pd( $\eta^{n}$ -C<sub>8</sub>H<sub>10</sub>)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], and -1.0 kcal/mol for [Pd( $\eta^{n}$ -C<sub>6</sub>F<sub>6</sub>)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (Table 4, columns d and e). The change in  $\Delta\Delta E_{int}$  is mainly attributable to a change in the orbital interaction energies  $\Delta\Delta E_{orb}$  on going from the ground state to the transition state (Table 4, column e).

The orbital interactions ( $\Delta E_{orb}$ ) in our systems are comprised of three different components: (i)  $\sigma$ donation interaction ( $\Delta E_{\sigma}$ ) from neutral ligand(s) to the Pd(Ar<sub>F</sub>)<sub>2</sub> fragment (column f, Table 4); (ii)  $\pi$ back-donation interaction ( $\Delta E_{\pi}$ ) from the Pd(Ar<sub>F</sub>)<sub>2</sub> fragment to neutral ligand(s) (column g, Table 4); and (iii) the rest of the orbital interactions ( $\Delta E_{orb(rest)}$ ), which mostly entails the electronic polarization within each fragment. The difference in the orbital interactions  $\Delta\Delta E_{orb}$  of cis-[PdL<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] is +15.5 kcal/mol for L = MeCN, +16.4 kcal/mol for L= THF, +16.1 kcal/mol for L = SMe<sub>2</sub> and +23.2 kcal/mol for L = PMe<sub>3</sub> (Table 4, column e). This significant reduction in  $\Delta E_{orb}$  in the transition states is mainly attributable to a decreased  $\sigma$ -interaction (Table 4, column f): (**3a**,  $\Delta\Delta E_{\sigma} = +20.6$  kcal/mol), THF (7,  $\Delta\Delta E_{\sigma} = +11.0 \text{ kcal/mol})$ ), SMe<sub>2</sub> (12,  $\Delta\Delta E_{\sigma} = +9.7 \text{ kcal/mol})$ ) and PMe<sub>3</sub> (16,  $\Delta\Delta E_{\sigma} = +21.6$ kcal/mol).  $\Delta\Delta E_{orb}$  increases by only a small amount (-1.1 - +6.9 kcal/mol) for [Pd( $\eta^n$ -Ar)(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>], as a result of the ring slippage and an increase in  $\pi$ -acceptance in the transition state, as the  $\pi$ -contribution becomes favorable by -9.4 kcal/mol for  $[Pd(\eta^n-C_6H_6)(C_6F_5)_2]$ , -9.3 kcal/mol for  $[Pd(\eta^n-C_7H_8)(C_6F_5)_2]$ , -8.2 kcal/mol for  $[Pd(\eta^n-C_8H_{10})(C_6F_5)_2]$ , and -13.4 kcal/mol for  $[Pd(\eta^n-C_6F_6)(C_6F_5)_2]$  (Table 4, columns e and g). Although the difference in orbital contributions  $\Delta\Delta E_{orb}$  in all cases can be explained using mainly the contributions from  $\sigma$  donation ( $\Delta\Delta E_{\sigma}$ ) and  $\pi$  back-donation ( $\Delta\Delta E_{\pi}$ ) interactions, impact from the rest of the orbital interactions ( $\Delta\Delta E_{orb(rest)}$ ) is also sizable (Table 4, column h), suggesting that there exist considerable polarization effects. The attractive energy contribution due to dispersion interactions, which arises from the attractive forces between the induced dipoles of the interacting fragments, in both reactant and transition state of all cases was found to be substantial albeit slightly less pronounced in the transition states (Table 4, column i). This contribution to the overall barrier is contained in  $\Delta E_{int}$ . Changes in the dispersion interaction  $\Delta \Delta E_{disp}$  play only a minor

role in the increase in the reductive elimination barrier, as the maximum difference between reactant and transition state is only +3.8 kcal/mol (Table 4, column i).

According to our calculations, the lower barrier for the complexes  $[Pd(\eta^n-Ar)(C_6F_5)_2]$  is due to: (i) ring slippage of the arene ligand and the adjustment of the arene ring to the electronic situation at the metal which leads to less  $\sigma$ -repulsion in the reductive elimination transition state; and (ii) to more favorable  $\pi$  back-bonding from Pd(Ar<sub>F</sub>)<sub>2</sub> to the arene fragment in the transition state. These factors lead to a lower lying transition state for  $[Pd(\eta^n-Ar)(C_6F_5)_2]$ . Furthermore, the 2e<sup>-</sup> donor ligands of  $[Pd L_2(C_6F_5)_2]$  stabilize the ground state much better than  $\eta^n$ -Ar ligand in  $[Pd(\eta^n-Ar)(C_6F_5)_2]$  and both factors, destabilization of the ground state of  $Pd(C_6F_5)_2$  and stabilization of the reductive elimination transition state of  $Pd(C_6F_5)_2$  for  $\eta^n$ -Ar in comparison to L, lead to a significantly reduced barrier for reductive elimination.

Overall, insights gained into the bonding interactions between various ligands and the  $Pd(Ar_F)_2$  fragment using the EDA-NOCV method suggest that it is the weakly donating and strongly accepting characters of arene ligands that minimize the reductive elimination barrier compared to stronger donor and weaker acceptor ligands L. Ligands such as MeCN, THF, SMe<sub>2</sub> and PMe<sub>3</sub> stabilize the (electron poor) Pd(II) ground state more efficiently than an arene ligand, whereas the arenes stabilize the developing charge in the transition state better than L. Both, destabilization of the ground state and stabilization of the transition state leads to lower barriers for the reductive elimination process.

**Catalytic cycle of the homocoupling reaction.** A plausible mechanism for the homocoupling reaction of fluorinated arylboronates conducted in arene solvent is depicted in Figure 13. Ag<sub>2</sub>O likely plays two roles. First, in the presence of trace moisture, it assists in the transmetalation process,<sup>5b,20c</sup> generating species **C** and two equivalents of HOBpin. The latter can condense yielding pinBOBpin, regenerating water. Second, following reductive elimination of the product biaryl from **C**, Ag<sub>2</sub>O oxidizes Pd(0) to Pd(II) to restart the cycle. Indeed, a silver mirror forms during the reaction.



Figure 13. Proposed mechanism for the palladium-catalyzed homocoupling of fluorinated arylboronates.

#### CONCLUSIONS

In summary, we demonstrated that the palladium-catalyzed homocoupling of highly fluorinated arylboronate esters containing two *ortho*-fluorine substituents does not proceed in coordinating solvents because the reaction stalls at the *cis*-[PdL<sub>2</sub>(Ar<sub>F</sub>)<sub>2</sub>] stage, as demonstrated by the isolation of the stable complexes *cis*-[Pd(MeCN)<sub>2</sub>(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub>] (**3a**), *cis*-[Pd(MeCN)<sub>2</sub>(2,4,6-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>)<sub>2</sub>] (**3b**), and *cis*-[Pd(MeCN)<sub>2</sub>(2,6-C<sub>6</sub>F<sub>2</sub>H<sub>3</sub>)<sub>2</sub>] (**3e**). This investigation also introduces the use of arylboronates instead of aryl Grignard or lithium substrates<sup>3,9</sup> to synthesize [PdL<sub>2</sub>(Ar<sub>F</sub>)<sub>2</sub>] complexes. Avoiding ligands and employing very weakly coordinating solvents ("non-coordinating") such as toluene, benzene or *m*xylene allows the catalytic homocoupling reaction to proceed smoothly, providing fluorinated biphenyl products.

DFT computations predict that catalytic homocoupling reactions of highly fluorinated arylboronate esters conducted in acetonitrile, THF, SMe<sub>2</sub> and PMe<sub>3</sub> are unfeasible, as the overall reductive elimination process is endergonic, and the reductive elimination step has a high barrier. While this is the case with strong  $\sigma$  donating solvents and ligands, computations indicate that coupling reactions carried out in aromatic solvents, which are, in general, weak  $\sigma$  donors and  $\pi$  acceptors, should be highly feasible, as the reductive elimination process is not only sufficiently exergonic, but also the overall barrier for reductive elimination was found to be <21 kcal/mol. The lower barrier for the reductive elimination from  $[(\eta^n-Ar)Pd(C_6F_5)_2]$  is due to: (i) ring slippage of the arene ligand and the adjustment of the arene ring to the electronic situation at the metal which leads to less  $\sigma$ -repulsion in the reductive elimination state; and (ii) more favorable  $\pi$  back-bonding from Pd(Ar<sub>F</sub>)<sub>2</sub> to the arene fragment in the transition state. Inspection of the reaction coordinates of the homocoupling process conducted in different solvents nicely explains our experimental results which showed that no catalysis takes place in acetonitrile and THF solvents, whereas catalytic homocoupling is efficient in aromatic solvents.

## Crystallographic details

Crystal data collection and processing parameters are given in the Supporting Information. CCDC-1939238 (2d), 1951276 (2f), 1939239 (3a), 1939240 (3b), 1953484 (3e) contain the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

# ASSOCIATED CONTENT

## **Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX.

Experimental and computational details and data (PDF)

Crystallographic data (CIF)

Cartesian coordinates of optimized structures (XYZ)

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#### Notes

The authors declare no competing financial interest.

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Dedicated to Prof. Robin N. Perutz, FRS on the occasion of his 70th birthday.

### **CONFLICT OF INTEREST**

The authors declare no conflict of interest.

Keywords: homogeneous catalysis; reductive elimination; palladium complexes; boron; fluorine

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# **Table of Contents**

