



# Weakly nucleophilic potassium aryltrifluoroborates in palladium-catalyzed Suzuki–Miyaura reactions: relative reactivity of $K[4-RC_6F_4BF_3]$ and the role of silver-assistance in acceleration of transmetallation

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## Full Research Paper

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## Abstract

Small differences in the reactivity of weakly nucleophilic potassium aryltrifluoroborates are revealed in the silver-assisted Pd-catalyzed cross-coupling of  $K[4-RC_6F_4BF_3]$  ( $R = H, Bu, MeO, EtO, PrO, iPrO, BuO, t-BuO, CH_2=CHCH_2O, PhCH_2O, PhCH_2CH_2O, PhO, F, pyrazol-1-yl, pyrrol-1-yl, \text{ and } indol-1-yl$ ) with  $ArX$  ( $4-BrC_6H_4CH_3, 4-IC_6H_4F$  and  $3-IC_6H_4F$ ). An assumed role of silver(I) compounds  $Ag_mY$  ( $Y = O, NO_3, SO_4, BF_4, F$ ) consists in polarization of the Pd–X bond in neutral complex  $ArPdL_nX$  with the generation of the related transition state or formation of  $[ArPdL_n][XAg_mY]$  with a highly electrophilic cation and subsequent transmetallation with the weakly nucleophilic borate. Efficiency of  $Ag_mY$  as a polarizing agent decreases in order  $Ag_2O > AgNO_3 \approx Ag_2SO_4 > Ag[BF_4] > AgF$ . No clear correlation between the reactivity of  $K[4-RC_6F_4BF_3]$  and substituent electron parameters,  $\sigma_I$  and  $\sigma_R^\circ$ , of the aryl group  $4-RC_6F_4$  was found.

## Introduction

The palladium-catalyzed reaction of organoboron compounds with C-electrophiles (Suzuki–Miyaura reaction) is one of the most intensively studied processes of the carbon–carbon bond formation. Organoboronic acids, their esters and organotrifluoroborates are partners in these reactions and the choice of

the desired reagent depends on the specific requirements in each particular case [1–3]. Organoboron reagents containing an electron-poor organic moiety exhibit a low reactivity under the usual cross-coupling conditions [3–9] and the target products are formed in low yield and/or are contaminated with byproducts.

Reactions of weakly nucleophilic organoboron reagents (alkyl- and cyclopropylboronic acids and esters [10–14], alken-1-ylboronic acids and esters [15,16], some arylboronic acids [17–19],  $K[CF_2=CFBF_3]$  [19]) often are accelerated by the addition of stoichiometric amounts of  $Ag_2O$ . Initially this phenomenon was reported by Kishi et al. [16] for the cross-coupling of alkenylboronic acids with alkenyl iodides in the presence of  $Ag_2O$  and elucidated by formation of  $AgOH$  which acts like aqueous  $KOH$  or  $TiOH$ . Korenaga et al. [20] have studied Pd-catalyzed cross-coupling of  $C_6F_5B(OH)_2$  with aryl halides in the presence of  $Ag_2O$  and assumed the generation of a hydroxy–palladium complex with higher ability to transmetalation under the action of the corresponding organoboron reagent than  $ArPdL_2X$ . For example, complex  $trans-C_6F_5Pd(PEt_3)_2OH$  is formed in the reaction of  $trans-C_6F_5Pd(PEt_3)_2I$  with  $Ag_2O$  in toluene–water and undergoes transmetalation with 4-MeOC<sub>6</sub>H<sub>4</sub>B(OH)<sub>2</sub> [21]. The subsequent reductive elimination leads to the corresponding polyfluorobiphenyl. In contrary, the reaction of  $trans-C_6F_5Pd(PEt_3)_2I$  with 2,4,6- $C_6F_3H_2B(OH)_2$  and  $Ag_2O$  leads to an unsymmetrical diarylpalladium complex  $trans-(C_6F_5)Pd(PEt_3)_2(2,4,6-C_6F_3H_2)$  in 92% yield. The latter is thermally stable and does not produce the cross-coupling product even upon heating in toluene at 100 °C for 24 h [21]. The authors suggested that acceleration of these reactions by silver(I) oxide results in the generation of a hydroxy–palladium complex with a higher ability to transmetalation, to coordinate to the organoboronic acid with the three-coordinated boron atom to  $ArPdL_2OH$  and subsequent transmetalation (Scheme 1).

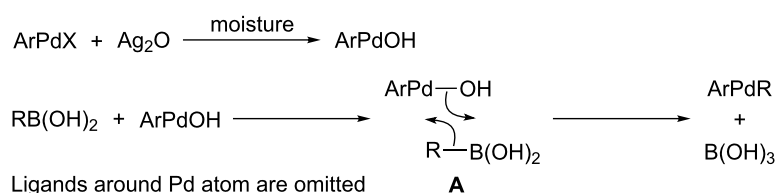
However, some experimental facts indicate the multilateral role of silver(I) compounds  $Ag_mY$  in the acceleration of the Suzuki–Miyaura cross-coupling. Beside generation of  $ArPdL_nOH$ ,  $Ag_mY$  may act as a Lewis acid producing complex  $[RPdL_n][XAg_mY]$  with a highly electrophilic cation. The reactions often are performed in polar aprotic solvents (MeCN, THF, acetone) and the complexes exist in solutions as solvates  $[RPdL_n(solv.)][XAg_mY]$ . Some complexes are much more stable and can be isolated [22,23], although for preparative aims they usually are generated in situ. This approach has been successfully used for arylation of alkenes, alkynes, insertion of CO species [23–31], polyfluoroarenes and thiophenes [32].

The effect of the counterion Y in silver(I) compounds  $Ag_mY$  on the rate of the cross-coupling was slightly investigated. For example, the rates of the CO insertion into cationic methylpalladium complex  $[MePd(PMe_3)_2][XAg_mY]$  generated from  $MePd(PMe_3)_2Cl$ ,  $Ag[BF_4]$  or  $Ag[PF_6]$  in acetone are equal to  $23 \cdot 10^{-5}$  and  $24 \cdot 10^{-5} s^{-1}$ . The use of  $AgOTf$  ( $11 \cdot 10^{-5} s^{-1}$ ) or  $AgNO_3$  ( $5.9 \cdot 10^{-5} s^{-1}$ ) causes a decrease in the reactivity towards the CO insertion [28,33]. The similar effect of anions  $Y = BF_4, OTf, PF_6$  was observed in the formation of complexes  $[RPd(PMe_3)_2(solv.)][XAg_mY]$  and  $[RPd(PMe_3)(solv.)_2][XAg_mY]$  [34].

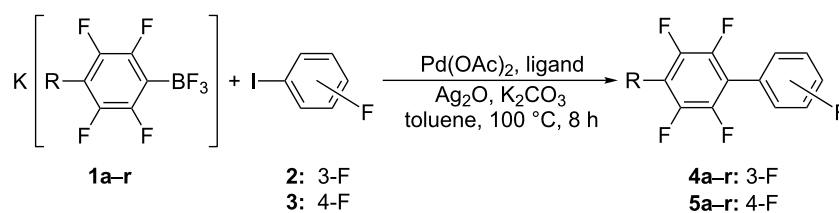
In continuation of systematic research of the Suzuki–Miyaura cross-coupling reaction of weakly nucleophilic organotrifluoroborates we report here the study of the relative reactivity of  $K[4-RC_6F_4BF_3]$  in the Pd-catalyzed reactions with some aryl bromides and iodides in the presence of  $Ag_2O$ . The borates were chosen as model organoboron reagents because of tuning electronic properties of 4- $RC_6F_4$  groups with varied  $R = H, Bu, MeO, EtO, PrO, iPrO, BuO, t-BuO, CH_2=CHCH_2O, PhCH_2O, Ph(CH_2)_2O, PhO, pyrazol-1-yl (Prz), pyrrol-1-yl (Pyr), indol-1-yl (Ind), imidazol-1-yl (Im),$  and benzamidazol-1-yl (Bim) and the equal steric requirements near reaction site  $C^1-BF_3$ . The relative reactivity was estimated (a) from the yield of biphenyl 4- $RC_6F_4-Ar$  vs  $C_6F_5-Ar$  and (b) from the rate of consumption of  $K[4-RC_6F_4BF_3]$  and compared with the substituent electron parameters (SEP) of the 4- $RC_6F_4$  group. The efficiency of some other silver(I) compounds ( $AgNO_3, Ag_2SO_4, Ag[BF_4],$  and  $AgF$ ) in the cross-coupling was examined too.

## Results

All reactions were carried out under the previously elaborated optimal conditions [35]. The cross-coupling of  $K[4-RC_6F_4BF_3]$  (**1a–r**) with 1-fluoro-3-iodobenzene (**2**) produces pentafluorobiphenyls 4-(3'- $FC_6H_4$ ) $C_6F_4R$  in 80–99% yield (Scheme 2 and Table 1). Pentafluorobiphenyls 4-(4'- $FC_6H_4$ ) $C_6F_4R$  were obtained from  $K[4-RC_6F_4BF_3]$  and 1-fluoro-4-iodobenzene (**3**). Notably borates  $K[4-RC_6F_4BF_3]$  with  $R = H$  (**1b**), AllylO (**1c**) and azolides (**1n–r**) (see Table 1, entries 2, 3, 14–18) give much lower yields of the corresponding biphenyls than  $K[C_6F_5BF_3]$  (**1a**) (Table 1, entry 1) [19].



**Scheme 1:** The assumed silver(I) oxide assisted transmetalation with organoboronic acids.



Ligand = PPh<sub>3</sub>; R = F (**a**), H (**b**), AllylO (**c**), MeO (**d**), EtO (**e**), PrO (**f**), Bu (**g**), PhCH<sub>2</sub>O (**h**), BuO (**i**), *i*PrO (**j**), *t*-BuO (**k**), Ph(CH<sub>2</sub>)<sub>2</sub>O (**l**), PhO (**m**), Ind (**n**), Pyr (**o**), Prz (**p**)

Ligand = XPhos; R = imidazol-1-yl (**l**m) (**q**), benzimidazol-1-yl (**B**im) (**r**)

**Scheme 2:** Cross-coupling of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] (**1a-r**) with 3-IC<sub>6</sub>H<sub>4</sub>F (**2**) and 4-IC<sub>6</sub>H<sub>4</sub>F (**3**).

**Table 1:** Preparation of biphenyls **4a-r** and **5a-r**.

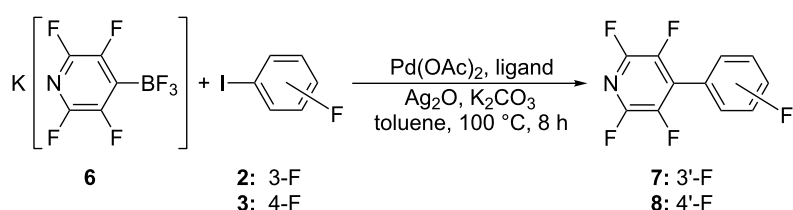
Entry	K[4-RC <sub>6</sub> F <sub>4</sub> BF <sub>3</sub> ]	Isolated yield (%)	
		<b>4</b>	<b>5</b>
1	<b>1a</b> (R = F)	99	99
2	<b>1b</b> (R = H)	26	24
3	<b>1c</b> (R = AllylO)	34	18
4	<b>1d</b> (R = MeO)	90	94
5	<b>1e</b> (R = EtO)	98	97
6	<b>1f</b> (R = PrO)	82	96
7	<b>1g</b> (R = Bu)	89	50
8	<b>1h</b> (R = PhCH <sub>2</sub> O)	86	73
9	<b>1i</b> (R = BuO)	87	99
10	<b>1j</b> (R = <i>i</i> PrO)	82	97
11	<b>1k</b> (R = <i>t</i> -BuO)	98	99
12	<b>1l</b> (R = Ph(CH <sub>2</sub> ) <sub>2</sub> O)	79	71
13	<b>1m</b> (R = PhO)	98	96
14	<b>1n</b> (R = Ind)	91	42
15	<b>1o</b> (R = Pyr)	84	20
16	<b>1p</b> (R = Prz)	47	35 <sup>a</sup>
17	<b>1q</b> (R = <i>l</i> m)	10 <sup>b, c</sup>	12 <sup>b, d</sup>
18	<b>1r</b> (R = <i>B</i> im)	20 <sup>b, e</sup>	20 <sup>b, f</sup>

<sup>a</sup>Byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>HPrz (3%); <sup>b</sup>phosphine XPhos was used instead of PPh<sub>3</sub>; <sup>c</sup>byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>H*l*m (7%); <sup>d</sup>byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>H*l*m (7%); <sup>e</sup>byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>H*B*im (5%); <sup>f</sup>byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>H*B*im (14%).

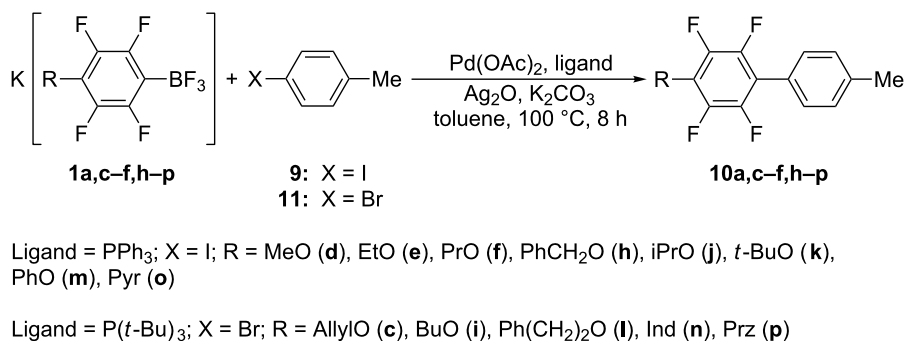
Potassium 2,3,5,6-tetrafluoropyridyltrifluoroborate (**6**) exhibits extremely low reactivity toward both **2** and **3** gives the corresponding 4-(3'-fluorophenyl)- (**7**) and 4-(4'-fluorophenyl)- (**8**) -2,3,5,6-tetrafluoropyridines with yields no more than 5% (<sup>19</sup>F NMR) (Scheme 3). It should be noted that 2,3,5,6-tetrafluoropyridine was not observed in the reaction mixtures in both cases.

The use of the electron-rich C-electrophile, 4-IC<sub>6</sub>H<sub>4</sub>CH<sub>3</sub> (**9**), instead of **3** leads to biphenyls 4-(4'-CH<sub>3</sub>C<sub>6</sub>H<sub>4</sub>)C<sub>6</sub>F<sub>4</sub>R (**10c-f, h-p**) in 60–80% preparative yields (see Table 2, entries 2–14) while 4-CH<sub>3</sub>C<sub>6</sub>H<sub>4</sub>C<sub>6</sub>F<sub>5</sub> (**10a**) was isolated in 93% yield (see Table 2, entry 1) [19]. Although aryl bromides are less reactive than iodides, the substitution of 4-IC<sub>6</sub>H<sub>4</sub>CH<sub>3</sub> (**9**) for 4-BrC<sub>6</sub>H<sub>4</sub>CH<sub>3</sub> (**11**) does not affect the yields of the corresponding biphenyls (Scheme 4).

The obtained results show a similar or slightly reduced reactivity of the majority of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] (R ≠ F) with respect to salt **1a**. Exceptions are borates with R = H (**1b**), CH<sub>2</sub>=CHCH<sub>2</sub>O (**1c**) and azolides (**1n-r**), which produce cross-coupling products in low to moderate yields because of the side reactions. Highly tolerant borate **6** also gives the product in a low yield, but its conversion is low too. Hence, the data based on an isolated yield of biphenyls **4a-r**, **5a-r**, or **10a, c-f, h-p** are not a



**Scheme 3:** Attempted synthesis of **7** (3'-F) and **8** (4'-F) by cross-coupling reaction.

Scheme 4: Synthesis of biphenyls **10a,c-f,h-p**.Table 2: Preparation of biphenyls **10a,c-f,h-p**.

Entry	K[4-RC <sub>6</sub> F <sub>4</sub> BF <sub>3</sub> ]	Isolated yield of <b>10</b> (%)	Entry	K[4-RC <sub>6</sub> F <sub>4</sub> BF <sub>3</sub> ]	Isolated yield of <b>10</b> (%)
1	<b>1a</b> (R = F)	93	8	<b>1j</b> (R = <i>i</i> PrO)	71
2	<b>1c</b> (R = AllylO)	25 <sup>a</sup>	9	<b>1k</b> (R = <i>t</i> -BuO)	62
3	<b>1d</b> (R = MeO)	80	10	<b>1l</b> (R = Ph(CH <sub>2</sub> ) <sub>2</sub> O)	93
4	<b>1e</b> (R = EtO)	70	11	<b>1m</b> (R = PhO)	65
5	<b>1f</b> (R = PrO)	83	12	<b>1n</b> (R = Ind)	91
6	<b>1h</b> (R = PhCH <sub>2</sub> O)	43 <sup>b</sup>	13	<b>1o</b> (R = Pyr)	73
7	<b>1i</b> (R = BuO)	97	14	<b>1p</b> (R = Prz)	99

<sup>a</sup>Byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>HOCH<sub>2</sub>CH=CH<sub>2</sub> (18%); <sup>b</sup>byproduct 2,3,5,6-C<sub>6</sub>F<sub>4</sub>HOCH<sub>2</sub>Ph (28%).

convenient measure for the quantitative estimation of the relative reactivity. We hoped to get more accurate data by the concurrent cross-coupling of equimolar mixtures of K[C<sub>6</sub>F<sub>5</sub>BF<sub>3</sub>] (**1a**) and K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] (**1b-p**) with **11**. The reactions were carried out over a short period (5–15 min) and the product ratios were determined by analyzing the crude reaction mixtures with <sup>19</sup>F NMR spectroscopy. The relative reactivity was determined as  $C^{\text{rel}} = C^{\text{R}} / C^{\text{F}}$  where  $C^{\text{R}}$  and  $C^{\text{F}}$  are the yield (in mmol) of 4-(4'-CH<sub>3</sub>C<sub>6</sub>H<sub>4</sub>)C<sub>6</sub>F<sub>4</sub>R from salts **1b-p** and 4'-CH<sub>3</sub>C<sub>6</sub>H<sub>4</sub>C<sub>6</sub>F<sub>5</sub> from **1a**, respectively (Scheme 5, Table 3).

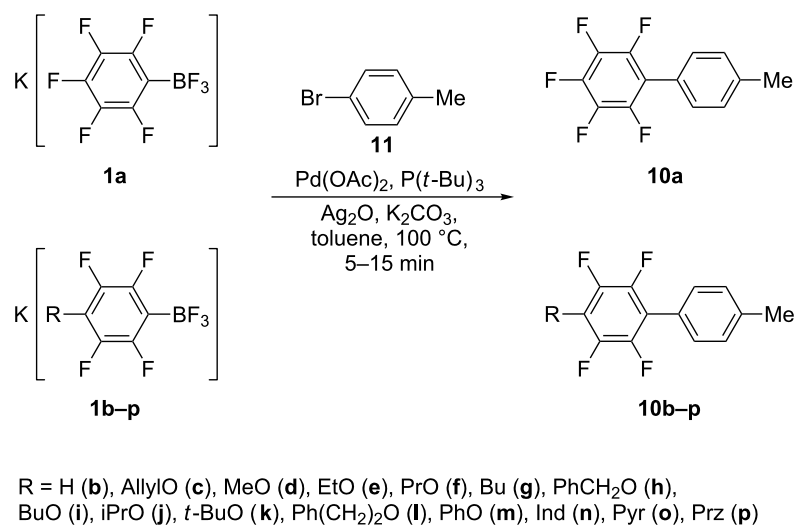
The above experiments were performed using silver(I) oxide. For better understanding the role of Ag<sup>+</sup> we estimated the relative efficiency of some other silver(I) compounds under identical conditions (Scheme 6) (Table 4).

The presented data demonstrate clearly that AgNO<sub>3</sub>, Ag<sub>2</sub>SO<sub>4</sub>, Ag[BF<sub>4</sub>], and AgF salts are less appropriate promoters for the palladium catalyzed cross-coupling than Ag<sub>2</sub>O. The significant contribution of the side reactions (hydrodeboration and homo-coupling) results in decreasing yields of **10a** and hinders isolation of the desired product (see Table 4).

## Discussion

The general concept of the Pd-catalyzed Suzuki–Miyaura (SM) reaction applied to the cross-coupling of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] with ArX is presented in Scheme 7.

The first step is the generation of neutral complex ArPdX by the oxidative addition of ArX to Pd(0) species. This step precedes the subsequent transformation of ArPdX and does not influence the reactivity of organoboron partner K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] as well as its behavior in transmetalation and/or reductive elimination steps. For the further consideration we need to clarify the nature of the active organoboron partner. Despite of many publications [2,6,7,36,37] in this field it is not yet fully understood. For illustration, we refer to two examples. Molander argues for direct transmetalation of ArPdBr by aryltrifluoroborates in aprotic anhydrous THF in the presence of trialkylamine as a base or in alcohols [4]. Alternatively, the Pd-catalyzed cross-coupling of K[ArBF<sub>3</sub>] in aqueous THF is proved to proceed through stepwise hydrolysis to produce more reactive [ArBF<sub>*n*</sub>(OH)<sub>3-*n*</sub>]<sup>−</sup> or ArB(OH)<sub>2</sub> [35,38]. However, special experiments showed that K[C<sub>6</sub>F<sub>5</sub>BF<sub>3</sub>] retards toward K<sub>2</sub>CO<sub>3</sub> [39] as well as K<sub>2</sub>CO<sub>3</sub> in a mixture with catalytic amounts of



**Scheme 5:** Pd-catalyzed cross-coupling of **1a** and salts **1b–p** (1:1) with **11** (the results are presented in Table 3 and outlined in the Discussion section).

**Table 3:** Relative reactivity  $C^{\text{rel}}$  of  $\text{K}[\text{4-RC}_6\text{F}_4\text{BF}_3]$  in the cross coupling with **11**.<sup>a,b</sup>

Entry	$\text{K}[\text{4-RC}_6\text{F}_4\text{BF}_3]$	$C^{\text{R}}$	$C^{\text{F}}$	$C^{\text{rel}}$
1	<b>1c</b> (R = AllylO)	13	22	0.59
2	<b>1g</b> (R = Bu)	27	40	0.68
3	<b>1f</b> (R = PrO)	22	32	0.68
4	<b>1d</b> (R = MeO)	22	29	0.76
5	<b>1h</b> (R = PhCH <sub>2</sub> O)	25	32	0.78
6	<b>1b</b> (R = H)	22	28	0.79
7	<b>1i</b> (R = BuO)	23	28	0.82
8	<b>1k</b> (R = <i>t</i> -BuO)	26	29	0.90
9	<b>1j</b> (R = <i>i</i> PrO)	23	25	0.92
10	<b>1e</b> (R = EtO)	31	33	0.94
11	<b>1m</b> (R = PhO)	20	21	0.95
12	<b>1n</b> (R = Ind)	26	27	0.96
13	<b>1l</b> (R = Ph(CH <sub>2</sub> ) <sub>2</sub> O)	22	22	1.00
14	<b>1o</b> (R = Pyr)	26	25	1.04
15	<b>1p</b> (R = Prz)	26	25	1.04

<sup>a</sup>Conditions:  $\text{Pd}(\text{OAc})_2$ ,  $\text{P}(t\text{-Bu})_3$ ,  $\text{Ag}_2\text{O}$ ,  $\text{K}_2\text{CO}_3$  in toluene, 100 °C, 5–15 min; <sup>b</sup> $C^{\text{rel}} = C^{\text{R}}/C^{\text{F}}$ , where  $C^{\text{R}} = 4\text{-(4'-CH}_3\text{C}_6\text{H}_4\text{)C}_6\text{F}_4\text{R}$  (mmol)/ $\text{K}[\text{4-RC}_6\text{F}_4\text{BF}_3]$  (0.20 mmol) and  $C^{\text{F}} = 4\text{-(4'-CH}_3\text{C}_6\text{H}_4\text{)C}_6\text{F}_5$  (mmol)/ $\text{K}[\text{C}_6\text{F}_5\text{BF}_3]$  (0.20 mmol).

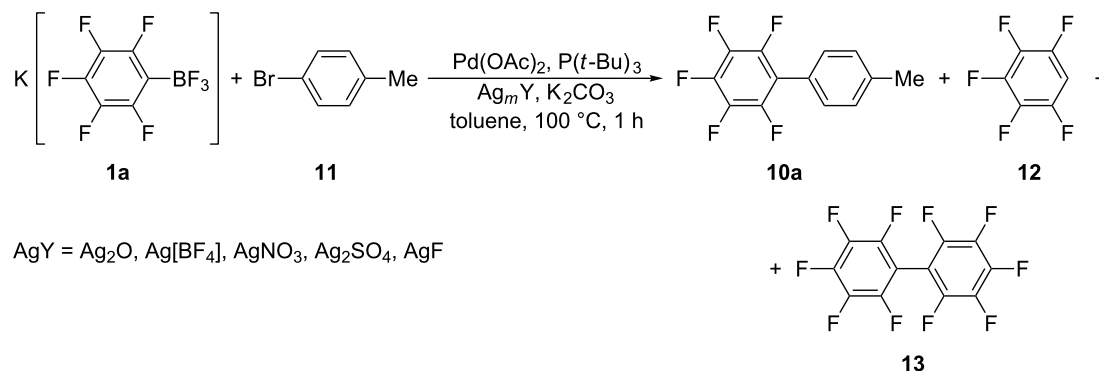
$\text{Pd}(\text{OAc})_2$  in refluxing MeOH [19]. Resistance of  $\text{K}[\text{C}_6\text{F}_5\text{BF}_3]$  (**1a**) towards  $\text{K}_2\text{CO}_3$  and  $\text{Ag}_2\text{O}$  in toluene (without palladium catalyst and phosphine ligand) is confirmed by stirring the corresponding suspensions at 100 °C for 10 min. These facts make it possible to reject any transformation of the  $[\text{BF}_3]^-$  moiety before the transmetalation of the palladium-containing intermediate generated in the previous step of the catalytic cycle by  $\text{K}[\text{4-RC}_6\text{F}_4\text{BF}_3]$ . Potassium carbonate scavenges toluene-

soluble acidic impurities formed in the reaction and does not participate in the other steps [19,35].

The boron atom in  $\text{K}[\text{4-RC}_6\text{F}_4\text{BF}_3]$  is coordinately saturated and transmetalation via transition state **A** (Scheme 1) is impossible. An alternative pathway is the polarization of the palladium–X bond by  $\text{Ag}^+$  and the generation of complex  $[\text{ArPdL}_n][\text{XAg}_m\text{Y}]$  with a highly electrophilic cation which is attacked by carbon atom C-1 of  $\text{K}[\text{C}_6\text{F}_5\text{BF}_3]$  (**1a**). In toluene salt **1a** is consumed within 3 h to give 2,3,4,4',5,6-hexafluorobiphenyl (**5a**) in 70–92% yield [19], while in the polar coordinating solvents (DME, DMF) the  $\text{Ag}_2\text{O}$ -assisted cross-coupling of **1a** with **3** leads to formation of **5a** at unsatisfactory conversions (22–38%) and low yields (10–22%). This indicates that the strong solvation of the Pd atom with DME or DMF reduces electrophilicity of  $[\text{ArPdL}_n][\text{X}]$  as compared with the electrophilicity in the case of weakly coordinating toluene.

$\text{K}[\text{C}_6\text{F}_5\text{BF}_3]$  (**1a**) and  $\text{Ag}_m\text{Y}$  are insoluble in toluene and, very likely, the transmetalation proceeds on the surface of the silver(I) compounds. Both the aryltrifluoroborate anion and  $\text{ArPdL}_n\text{X}$  can be adsorbed on the surface of solid  $\text{Ag}_m\text{Y}$  due to the interaction with Ag atoms (acidic Lewis centers). This phenomenon causes an increase in the electrophilicity of the Pd atom and bond rearrangement through transition state **B** to give the diarylpalladium species (Scheme 8). Perhaps, transformations presented in Scheme 8 are parallel, i.e., the transmetalation proceeds simultaneously with polarization of  $\text{ArPdL}_n\text{X}$ .

There is a popular notion that the transmetalation gives both *cis*- and *trans*- $\text{ArPdL}_n\text{Ar}'$ . First of them is low stable and under-

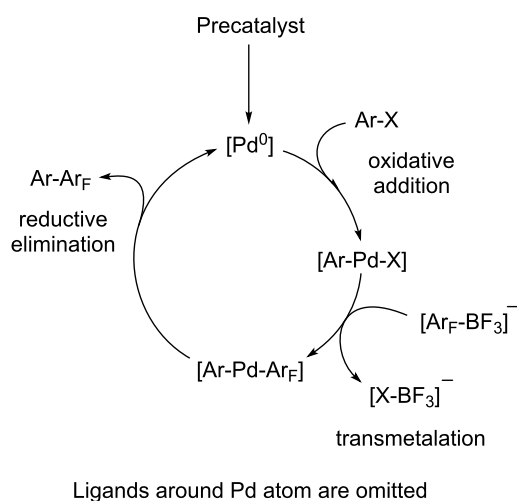


**Scheme 6:** The cross-coupling of **1a** with **11** in the presence of different silver(I) compounds.

**Table 4:** Cross-coupling of **1a** with **11** in the presence of different silver(I) compounds.

Entry	Conversion of <b>1a</b> (%)	Ag <sub>m</sub> Y	Yield (%) <sup>a,b</sup>		
			<b>10a</b>	<b>12</b>	<b>13</b>
1	69	Ag <sub>2</sub> O	99	1	0
2	79	AgNO <sub>3</sub>	20	27	27
3	75	Ag <sub>2</sub> SO <sub>4</sub>	20	28	26
4	40	Ag[BF <sub>4</sub> ]	40	60	0
5	19	AgF	51	43	3

<sup>a</sup>Yields were determined by <sup>19</sup>F NMR; <sup>b</sup>calculated on reacted **1a**.



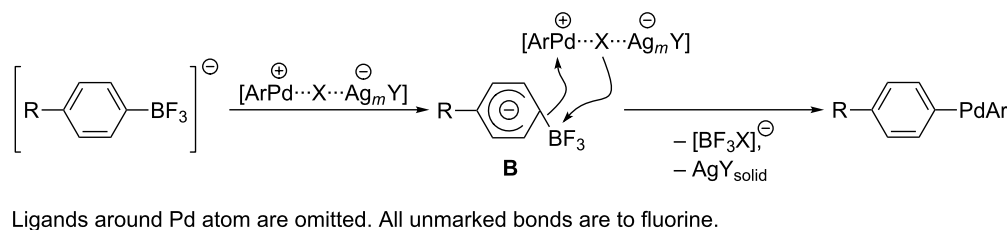
**Scheme 7:** General concept of Pd-catalyzed Suzuki–Miyaura reaction.

goes easy reductive elimination to biphenyl. *trans*-ArPdL<sub>*n*</sub>Ar' can react only after transformation to the corresponding *cis*-isomer [40,41]. Complexes with polyfluorinated aryl groups are highly stable and do not isomerize to the *cis*-isomer as well as do not form the cross-coupling products. Thus, independently

prepared complexes *trans*-C<sub>6</sub>F<sub>5</sub>PdL<sub>2</sub>(2,4,6-C<sub>6</sub>F<sub>3</sub>H<sub>2</sub>) (L = PEt<sub>3</sub>, PMe<sub>2</sub>Ph, PMePh<sub>2</sub>) do not undergo any changes even after heating in toluene at 100 °C for 24 h [21]. These facts lead to assume either instability of *trans*-(4-RC<sub>6</sub>F<sub>4</sub>)PdL<sub>2</sub>Ar towards isomerisation to *cis*-isomer or the direct formation of reactive complex *cis*-(4-RC<sub>6</sub>F<sub>4</sub>)PdL<sub>2</sub>Ar during the transmetalation with closely related borates K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] (Scheme 8).

At the next step, *cis*-(4-RC<sub>6</sub>F<sub>4</sub>)PdL<sub>2</sub>Ar undergoes reductive elimination which includes the carbon–palladium bond cleavage in both 4-RC<sub>6</sub>F<sub>4</sub>-Pd and Pd-Ar moieties. If the substituent Ar is the same for all *cis*-diarylpalladium, the rate of the intramolecular transformation from *cis*-(4-RC<sub>6</sub>F<sub>4</sub>)PdL<sub>2</sub>Ar to 4-RC<sub>6</sub>F<sub>4</sub>Ar should depend on the specific property of the 4-RC<sub>6</sub>F<sub>4</sub> group. It may depend on the substituent electron parameters (SEP), σ<sub>I</sub> and σ<sub>R</sub><sup>o</sup>, of substituent R or 4-RC<sub>6</sub>F<sub>4</sub> groups. We compared the relative rates of consumption C<sup>rel</sup> (Table 3) of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] with σ<sub>I</sub> (R) and σ<sub>R</sub><sup>o</sup> (R) (Table 5) and did not find any correlation between the obtained values.

SEP of the 4-RC<sub>6</sub>F<sub>4</sub> groups are not reported as yet except inductive constants σ<sub>I</sub> (C<sub>6</sub>F<sub>5</sub>) [43,45,46] and σ<sub>I</sub> (2,3,5,6-C<sub>6</sub>F<sub>4</sub>H) [43], and resonance constants σ<sub>R</sub><sup>o</sup> (C<sub>6</sub>F<sub>5</sub>) [45]. We bridge this gap using a series of biphenyls **4a–r** and **5a–r** and determine SEP of 4-RC<sub>6</sub>F<sub>4</sub> groups using the Taft's method [42]. The <sup>19</sup>F NMR spectra were measured in CHCl<sub>3</sub> (non-polar weakly coordinating solvent) and in toluene (solvent for the present research). The calculated SEP values in both solvents are closely related to one another to indicate no specific intermolecular interaction biphenyl–solvent (Table 6) and obtained results are in agreement with the data by Sheppard for CCl<sub>3</sub>F or benzene [45]. When R = H, Bu, or alkoxy group, inductive constants σ<sub>I</sub> (4-RC<sub>6</sub>F<sub>4</sub>) consist of 0.16–0.18. The 4-RC<sub>6</sub>F<sub>4</sub> groups with R = F, pyrazol-1-yl, pyrrol-1-yl, indol-1-yl, imidazol-1-yl and benzimidazol-1-yl possess a higher electron-withdrawing effect (σ<sub>I</sub> = 0.21 – 0.27) which achieves maximum



**Scheme 8:** Assumed silver(I)-assisted transmetalation of weakly nucleophilic arytrifluoroborates.

**Table 5:** The substituent electron parameters of some R in RC<sub>6</sub>H<sub>4</sub>F (in CDCl<sub>3</sub>) [42].

R	H	Bu [43]	OCH <sub>3</sub>	Prz [44]	Pyr [44]	F	Im [44]
σ <sub>I</sub>	0	0.01	0.29	0.300	0.354	0.45	0.513
σ <sub>R</sub> <sup>o</sup>	0	-0.18	-0.56	-0.061	-0.210	-0.39	-0.155

**Table 6:** The substituent electron parameters (SEP) of 4-RC<sub>6</sub>F<sub>4</sub> groups.

R	σ <sub>I</sub>		σ <sub>R</sub> <sup>o</sup>	
	In toluene	In CHCl <sub>3</sub>	In toluene	In CHCl <sub>3</sub>
4-PhCH <sub>2</sub> O	0.160	0.172	0.010	0.014
4- <i>i</i> PrO	0.161		0.009	
4-PrO	0.163		0.008	
4- <i>t</i> -BuO	0.163	0.165	0.011	0.015
4-BuO	0.164	0.165	0.008	0.011
4-EtO	0.165	0.167	0.008	0.011
4-Bu	0.165	0.158	0.013	0.015
4-AllylO	0.166		0.010	
4-MeO	0.168		0.009	
4-PhCH <sub>2</sub> CH <sub>2</sub> O	0.170		0.008	
4-H <sup>a</sup>	0.179	0.193		0.029
4-PhO	0.201	0.211	0.021	0.023
4-Prz	0.214	0.253	0.033	0.037
4-Pyr	0.218	0.240	0.027	0.030
4-F <sup>b</sup>	0.220	0.235	0.022	0.025
4-Ind	0.235	0.250	0.032	0.034
4-Im	0.260		0.036	
4-Bim	0.270	0.293	0.040	0.044
4-CF <sub>3</sub> C <sub>6</sub> F <sub>4</sub>		0.300		0.056
4-C <sub>5</sub> NF <sub>4</sub>		0.346		0.064
2-C <sub>5</sub> NF <sub>4</sub>		0.248		0.070

<sup>a</sup>σ<sub>I</sub> = 0.33 (water, 25 °C) [43]; <sup>b</sup>σ<sub>I</sub> = 0.31 (water, 25 °C) [43,46], 0.25 (CCl<sub>3</sub>F) [45]; σ<sub>R</sub><sup>o</sup> = 0.02 (CCl<sub>3</sub>F) [45].

for the 2,3,5,6-tetrafluoropyridyl group (σ<sub>I</sub> = 0.35). Resonance constants σ<sub>R</sub><sup>o</sup> of all tetrafluoroaryl groups are insignificant and reflect the substantial non-coplanarity of aryl moieties [45].

Unfortunately, the search for possible dependence between the relative rates of consumption of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] and SEP of the respective 4-RC<sub>6</sub>F<sub>4</sub> group does not show certain correlation.

## Conclusion

1. The relative reactivities of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] in the Ag(I)-assisted Pd-catalyzed cross-coupling reactions with 3-IC<sub>6</sub>H<sub>4</sub>F, 4-IC<sub>6</sub>H<sub>4</sub>F, 4-IC<sub>6</sub>H<sub>4</sub>CH<sub>3</sub> or 4-BrC<sub>6</sub>H<sub>4</sub>CH<sub>3</sub> in the presence of P(*t*-Bu)<sub>3</sub> or PPh<sub>3</sub> (toluene, 100 °C, 8 h) differ negligibly from each other. The same results show the competitive cross-coupling of mixtures of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] and K[C<sub>6</sub>F<sub>5</sub>BF<sub>3</sub>] (1:1, mol) with 4-BrC<sub>6</sub>H<sub>4</sub>CH<sub>3</sub> at a low conversion of borates (<40%). K[2,3,5,6-C<sub>5</sub>NF<sub>4</sub>BF<sub>3</sub>] is extremely weakly nucleophilic and conversion in the cross-coupling product is no more than 5% in 8 h.

2. It is very likely that transmetalation of ArPdL<sub>n</sub>X with K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] proceeds on the surface of the silver(I) compounds (K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] and Ag<sub>m</sub>Y are insoluble in toluene). Neutral complex ArPdL<sub>n</sub>X is adsorbed on the acidic center (Ag<sup>+</sup>) of the solid surface to form highly reactive complex [ArPdL<sub>n</sub>⋯X⋯Ag<sub>m</sub>Y] which facilitates exchange of group BF<sub>3</sub> in K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] by ArPdL<sub>n</sub> and thus accelerates the formation of (4-RC<sub>6</sub>F<sub>4</sub>)PdL<sub>n</sub>Ar.

3. Verification of the assumed correlation between reactivity (C<sup>rel</sup>) of K[4-RC<sub>6</sub>F<sub>4</sub>BF<sub>3</sub>] and the substituent electron parameters (SEP) (σ<sub>I</sub> and σ<sub>R</sub><sup>o</sup>) as the measure of the electron-withdrawing properties of 4-RC<sub>6</sub>F<sub>4</sub> gives an unclear result. Intervals of change of both C<sup>rel</sup> (0.6–1.0) and σ<sub>I</sub> (0.16–0.27) are too narrow and small experimental errors of measurements may

corrupt or mask electronic effect of 4-RC<sub>6</sub>F<sub>4</sub> with respect to C<sub>6</sub>F<sub>5</sub> group.

## Supporting Information

### Supporting Information File 1

Full experimental details and compound characterization data.

[<http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-11-68-S1.pdf>]

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