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B-Alkyl Suzuki−Miyaura Cross-Coupling Reactions with Air-Stable Potassium Alkyltrifluoroborates

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Received March 12, 2003

The palladium-catalyzed cross-coupling reaction of substituted potassium alkyltrifluoroborates with aryl halides and aryl triflates proceeds readily with moderate to good yields. The potassium alkyltrifluoroborates **1**, **2**, and **3a**−**e** were easily synthesized and obtained as air-stable crystalline solids that can be stored for long periods of time. All of the cross-couplings proceed under the same reaction conditions using $PdCl_2(dppf)\cdot CH_2Cl_2$ as catalyst in THF−H_2O in the presence of 3 equiv of Cs_2CO_3 as base.

Introduction

The Suzuki−Miyaura[1] cross-coupling reaction has become one of the mildest and most versatile methods for metal-mediated carbon−carbon bond formation.[2] In recent years, enormous interest has emerged in the alkylboron version of this reaction.[3] The numerous natural products and analogues that have been synthesized via *B*-alkyl Suzuki−Miyaura coupling corroborate the value of this method.[4]

In comparison to other alkyl−metal cross-coupling reactions,[5,6,7] alkylboron derivatives offer substantial advantages: ready availability and facile access to the alkylboron component, easy incorporation of nontransferable boron ligands, tolerance of a broad range of functional groups in the coupling process itself, and easy separation of the nontoxic inorganic byproducts of the reaction.

Trialkylboranes (R_3B)[1a,b,8] have been employed extensively in the Suzuki cross-coupling reaction. Hydroboration with 9-BBN followed by cross-coupling of the *B*-alkyl 9-BBN derivatives comprises one of the most common procedures. However, the scope of coupling reactions employing these latter organoboron compounds presents characteristic problems including intolerance to some functionality (e.g., ketones) in the preparation of the boranes, air sensitivity, and a lack of atom economy.[9]

Alkylborinate esters (R_2BOR),[10] alkylboronic acids [$RB(OH)_2$], or boronic esters [$RB(OR')_2$] can also be employed as coupling partners. Initial results with alkylboronic esters (which also suffer from a lack of atom economy) provided very low yields in *B*-alkyl Suzuki coupling[8b] unless highly toxic thallium compounds (TlOH or Tl_2CO_3) were utilized as a base for the reaction.[11] Aside from cyclopropylboronic esters[12] (as well as cyclopropylboronic acids[13]), which possess significant sp^2-carbon character, relatively few other reports utilizing boronate esters have appeared. In one such contribution, a palladium−imidazolium carbene system[14] has been shown to be efficient

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10.1021/jo0343331 CCC: $25.00
Published on Web 06/05/2003

for the *B*-alkyl Suzuki−Miyaura reaction between alkylboronic esters and aryldiazonium tetrafluoroborates, providing the desired coupled product in moderate to good yields.

Since the early reports of cross-coupling reactions utilizing alkylboronic acids wherein yields of 20−30% were common,[15] considerable improvements in this arena have been achieved. Falck and co-workers have reported highly successful cross-couplings using a variety of alkylboronic acids and electrophiles, but 2.5 equiv of expensive silver oxide was required as an additive.[16] Our group reported the *B*-alkyl Suzuki−Miyaura reaction of alkylboronic acids with various aryl halides and aryl triflates in the presence of $PdCl_2(dppf)\cdot CH_2Cl_2$ as a catalyst and Cs_2CO_3 as base.[17] The reaction occurs without the use of toxic additives with satisfactory yields. However, it is well-known that boronic acids often pose problems owing to variable shelf lives. Boronic esters are often prepared as a means to purify the organoboron species, but some of these are hydrolytically stable and the diols used to create them are difficult to remove to regenerate the boronic acid.

In addition to these broadly based concerns, the cross-coupling of specific alkyl groups either remain problematic or have been ignored. For example, coupling of the methyl group with various organic halides is less than ideal.[16,18] In one report, 40 mol % of triphenylarsine was required for the cross-coupling reaction of methylboronic acid.[19] Tetramethyltin is quite toxic and *B*-methyl-9-BBN is spontaneously flammable. Methylborinate esters[10] have been utilized to carry out Suzuki coupling reactions with a variety of electrophilic substrates, but their syntheses are quite involved and again atom economy remains an issue. Copper-promoted[20] coupling reactions show promise, but beyond this there are really few alternatives. Another attractive alkyl chain for incorporation by coupling is the trialkylsilylmethyl derivative.[16,21,22]

Although many of the recent efforts to improve the Suzuki coupling reaction have focused on the development of new metal/ligand systems that could facilitate the cross-coupling and broaden its scope,[8c,d,23] organotrifluoroborates have surfaced as promising new reagents.[24] Potassium organotrifluoroborates (RBF_3K) can be easily prepared on large scale (>200 g) by the addition of KHF_2 to a variety of organoboron intermediates such as boronic acids, boronic esters, organodihaloboranes, or even organodiaminoboranes (eq 1). Potassium hydrogen fluoride is an inexpensive source of fluoride. Furthermore, the potassium trifluoroborates obtained are monomeric solids that are readily isolated and can be stored on the shelf for long periods of time.

$$RBX_2 + 2KHF_2 \xrightarrow{\text{solvent (aq)}} RBF_3K + 2HX + KF \qquad (1)$$

X = Halogen, OH, OR, NR_2

Palladium-catalyzed coupling reactions with these "ate" complexes were initially investigated with a limited range of electrophiles, such as arenediazonium tetrafluoroborates[25] or diaryliodonium salts.[26] Previous work in our laboratory demonstrated the feasibility of the cross-coupling reaction of potassium alkyl-,[27] alkenyl-,[28] and alkynyltrifluoroborates[29] with several aryl and alkenyl halides and triflates, using $PdCl_2(dppf)\cdot CH_2Cl_2$ (9 mol %) as a catalyst in the presence of Cs_2CO_3 or Et_3N. Furthermore, potassium aryl- and heteroaryltrifluoroborates[30] were found to be excellent partners in the reaction under ligandless palladium-catalyzed conditions, using K_2CO_3 as base in methanol or water in an open atmosphere. Batey and Quach have also reported similar coupling processes using tetraalkylammonium trifluoroborates.[31]

The value of these salts lies in their greater nucleophilicity,[32] air stability, and easy accessibility by a variety of techniques (including transmetalation from other organometallics,[33] as well as hydroboration), thereby combining the best features of *B*-alkyl-9-BBN compounds and alkylboronic acids and esters. In addition, the organotrifluoroborates are environmentally friendly. They are more atom-economical than most organoborons used in coupling reactions, and water may be used as a solvent or cosolvent, minimizing the amount of organic solvent.

In a previous report, we demonstrated that potassium alkyltrifluoroborate, with pendant cyano, bromo, ketone,

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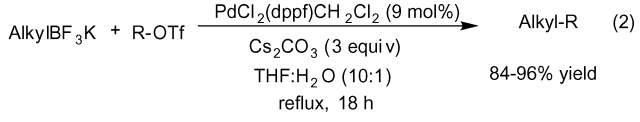
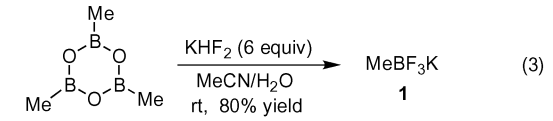
and ester groups, participates in the cross-coupling reaction with good yields (eq 2).[27]

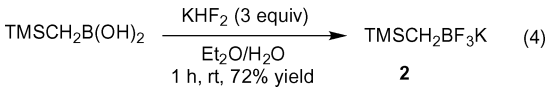


The promise of this class of reagents, along with the growing interest in the *B*-alkyl Suzuki−Miyaura reaction, moved us to explore the syntheses and cross-coupling processes of new potassium alkyltrifluoroborates. The results of these studies are reported herein.

Results and Discussion

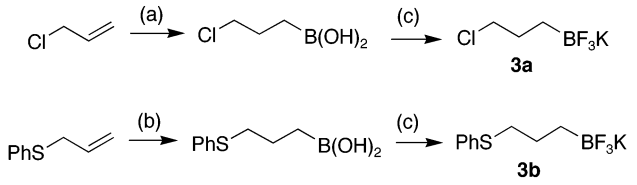
The required alkyltrifluoroborates were easily synthesized by the addition of KHF_2 to the corresponding boronic acid or ester.[24] Potassium methyltrifluoroborate was prepared from commercially available trimethylboroxine by addition of KHF_2 at room temperature in $MeCN/H_2O$ solution (eq 3). Potassium trimethylsilylmethyltrifluoroborate was obtained from the corresponding boronic acid[21,34] by treatment with KHF_2 in ether/H_2O solution. The desired potassium trifluoroborate salt **2** was obtained in 72% yield (eq 4).





Potassium 3-substituted-propyltrifluoroborates **3a**−**d** were synthesized from the corresponding allyl derivatives following established literature protocols for hydroboration of alkenes (Schemes 1 and 2).[35−37] Thus, hydroboration of allyl chloride was conducted using dichloroborane,[35] prepared from boron trichloride and triethylsilane at −78 °C. After aqueous workup the corresponding boronic acid was obtained. Allyl phenyl sulfide was hydroborated[36] with dibromoborane dimethyl sulfide complex, followed by hydrolysis to yield the boronic acid. Each boronic acid was treated with KHF_2 at room temperature in a mixture of ether/H_2O as solvent. After purification by crystallization in the appropriate solvent, potassium 3-chloropropyltrifluoroborate **3a** was obtained in 66% overall yield, and potassium 3-phenylthiopropyltrifluoroborate **3b** in 70% overall yield (Scheme 1).

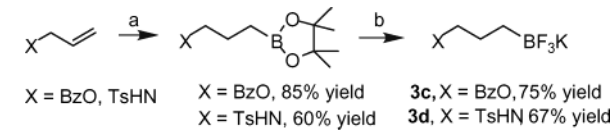
SCHEME 1[a]



[a] (a) $HSiEt_3$, BCl_3, CH_2Cl_2, −78 °C, 30 min, then H_2O/ether, 0 °C, 75% yield. (b) $HBBr_2{\cdot}Me_2S$ (2 equiv), CH_2Cl_2, reflux, 24 h, then H_2O/ether, 0 °C, 80% yield. (c) KHF_2 (3 equiv), ether/H_2O, rt, 1 h, 90% yield **3a**, 93% yield **3b**.

Allyl alcohol and allylamine first were protected as benzyloxy and tosylamide derivatives, respectively, following established protocols.[38] Catalytic hydroboration[37] with pinacolborane was used to perform the hydroboration.[39] The corresponding boronic ester obtained in this way was purified by column chromatography. Subsequent addition of KHF_2 to an $MeCN/H_2O$ solution of the boronic ester and purification by crystallization afforded the corresponding potassium alkyltrifluoroborates in 75% and 67% yield for **3c** and **3d**, respectively (Scheme 2). Potassium 3-phenylsulfonylpropyltrifluoroborate **3e** was obtained previously in our laboratories by *m*-CPBA oxidation of **3d**.[40] All of the potassium alkyltrifluoroborates prepared were air-stable powders or crystalline solids.

SCHEME 2[a]



[a] (a) Pinacolborane (1.5 equiv), $RhCl_2(PPh_3)_3$ (1%), CH_2Cl_2, rt, 24 h. (b) KHF_2 (3 equiv), $MeCN/H_2O$, rt, 1 h.

With these alkyltrifluoroborates in hand, we began the study of the cross-coupling reactions. As a starting point, potassium methyl- and trimethylsilylmethyltrifluoroborate coupling reactions were conducted with 4-acetylphenyltriflate. Fortunately, the conditions that we found to be optimal for Suzuki coupling of alkyltrifluoroborates (eq 2)[27] were also effective for **1** and **2**. Other bases (K_2CO_3 or Et_3N) and solvents (MeOH, dioxane, nonaqueous THF) were tested, but all combinations afforded lower yields of the coupled product. Thus, cross-couplings were carried out with different aryl triflates and halides using $PdCl_2(dppf){\cdot}CH_2Cl_2$ (9 mol %) and 3 equiv of Cs_2CO_3 as base, under reflux in THF/H_2O (20:1). It was determined to be necessary to perform all of these reactions under an inert atmosphere.

As outlined in Table 1, the cross-coupling reaction turned out to be general with respect to a diverse array of functionality. Methylation of the 4-acetyl and 4-nitrophenyl triflate (Table 1, entries 1 and 4) provided the desired coupled products in 85% yield, the same or even

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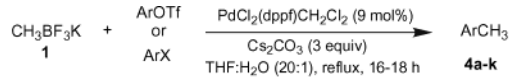
(39) Notes: Hydroboration with $HBBr_2{\cdot}SMe_2$ has also been performed for allyl alcohol protected as a benzyl, TBDMS, or TMS ether, but although hydroboration proceeded satisfactorily, problems in the KHF_2 step were found. BOC-*N*-allylamine was also tested under the $HBBr_2{\cdot}SMe_2$ hydroboration conditions, but starting material was recovered.
(40) Molander, G. A.; Ribagorda, M. Submitted for publication.

TABLE 1. Cross-Coupling Reaction of Potassium Methyltrifluoroborate 1



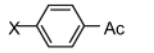
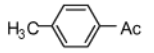
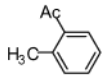
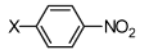
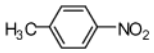
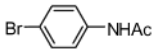
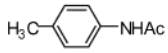
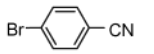
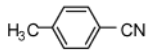
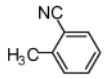
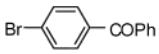
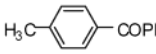
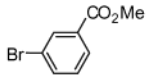
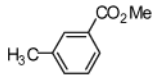
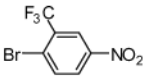
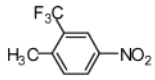
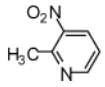
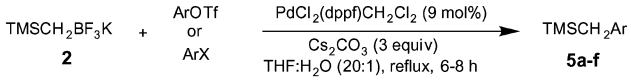
entry	ArBr or ArOTf	product	**4**, % isolated yield
1			**4a**, 85 (X = OTf)
2			80 (X = Br)
3			**4b**, 61
4			**4c**, 85 (X = OTf)
5			77 (X = Br)
6			**4d**, 67
7			**4e**, 68
8			**4f**, 60
9			**4g**, 92
10			**4h**, 57
11			**4i**, 85
12			**4j**, 83
13			**4k**, 32

TABLE 2. Cross-Coupling Reaction of Potassium Trimethylsilylmethyltrifluoroborate 2



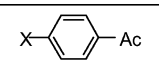
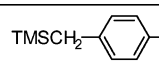
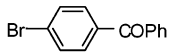
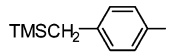
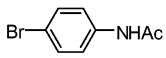
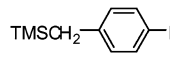
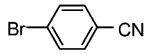
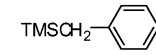
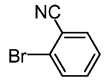
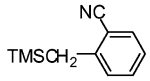
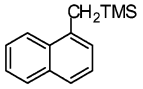
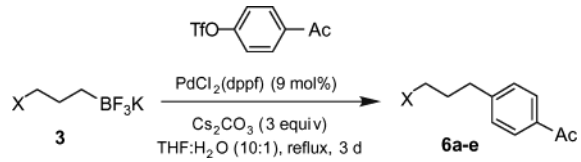
entry	ArBr or ArOTf	product	**5**, % isolated yield
1			**5a**, 70 (X = OTf)
2			65 (X = Br)
3			**5b**, 60
4			**5c**, 53
5			**5d**, 55
6			**5e**, 51
7			**5f**, 77

TABLE 3. Cross-Coupling Reaction of Potassium 3-Substituted-Propyltrifluoroborates 3 with 4-Acetylphenyltriflate



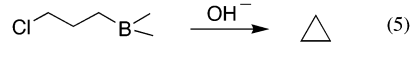
entry	RBF_3K	X	product	% yield[a]
1	**3a**	Cl	**6a**	72[b]
2	**3b**	PhS	**6b**	66[c]
3	**3c**	BzO	**6c**	70[b]
4	**3d**	TsNH	**6d**	75[b]
5	**3e**	$PhSO_2$	**6e**	70[b]

[a] Isolated yield. [b] 5−10% of homocoupling of the triflate partner was detected by GC in the crude reaction mixture. [c] 15% of homocoupling of the triflate partner was detected by GC in the crude reaction mixture.

better yields than those obtained in the best procedures reported previously.[15,16] Aryl triflates showed a slight increase in reactivity as compared to aryl bromides (Table 1, entries 1 and 2, 4 and 5). This effect in the reactivity has been observed before.[17,27] Regarding substitution on the aryl moiety, better yields were obtained with *para* than with *ortho*-aryl derivatives, probably for steric reasons (Table 1, entries 2 and 3, 7 and 8). Except for the low yield observed in the case of the heteroaryl chloride (entry 13), in general methylation using potassium methyltrifluoroborate **1** proceeds readily with satisfactory yield. Compatibility was demonstrated with cyano, ketone, ester, amide, and nitro groups despite the aqueous basic conditions.

The cross-coupling reactions of potassium alkyltrifluoroborate **2** with different aryl electrophiles are summarized in Table 2. The conditions of the reaction are the same as above, but shorter reaction times were used (6−8 h). Longer reaction times afforded the methyl-coupled product as a consequence of the cleavage of the TMS functional group.[41] As was observed before, 4-acetylphenyltriflate gave a better yield (70%) than the corresponding bromo derivative (65%) (Table 2, entries 1 and 3). Moderate yields were obtained with the 4-cyano- and 4-acetamidophenyl bromides.

The reaction of 3-halopropylboranes with base leads to the synthesis of cyclopropanes (eq 5).[42] Consequently, it could be anticipated that such reagents would prove problematic in Suzuki coupling reactions. However, we have found that potassium 3-chloropropyltrifluoroborate **3a** can be utilized effectively in the coupling process, despite the basic conditions of the reaction (Table 3).



(5)

The Suzuki−Miyaura reaction was carried out using 4-acetylphenyltriflate as the coupling partner. Once

(41) For example, when **2** reacted with 4-acetylphenyltriflate, after 8 h the major compound was **5a** (isolated in 65% yield), and a reaction time of 18 h afforded a 70% of the 4-acetyltoluene **4a**.

(42) (a) Hawthorne, M. F.; Dupont, J. A. *J. Am. Chem. Soc.* **1958**, *80*, 5830−5832. (b) Brown, H. C.; Rhodes, S. P. *J. Am. Chem. Soc.* **1969**, *91*, 2149−2150.

again, the best conditions found were the common ones for the alkyltrifluoroborates, using $PdCl_2(dppf)$[43] (9 mol %) with 3 equiv of Cs_2CO_3 as base in THF/H_2O (10:1) heated at reflux. Attempts to change the base (K_2CO_3, TfOK, Et_3N, DMAP) or solvent (DME, dioxane, MeOH, *i*-PrOH, MeCN, DMF) under either anhydrous or aqueous conditions gave poor yields of the desired product.

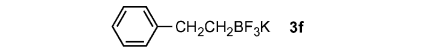
As indicated in Table 3, chloride-, nitrogen-, oxygen-, and even sulfur-based functional groups are compatible in the cross-coupling process, affording good yields of coupled products. Longer reaction times (3 d) were required in comparison to other alkyltrifluoroborates. Analysis by gas chromatography during the course of the reaction showed a clean evolution of the desired products and 5−15% of homocoupled product of the aryl triflate, probably as a consequence of the longer reaction times needed.

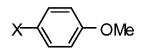
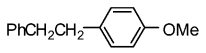
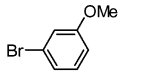
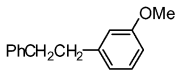
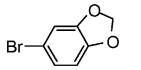
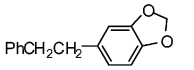
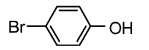
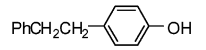
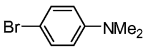
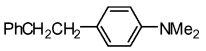
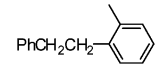
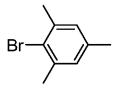
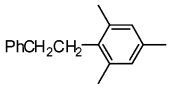
The reactions of some electron-rich electrophiles proved more difficult. In general, for such coupling partners 18 h were enough for the formation of the desired products.[44] Additional time only increased the amount of protodeboronated and protodehalogenated byproducts, and different proportions of homocoupling of the electrophile, protodehalogenation, and protodeboronation were observed in all of these examples. When 2-phenylethyltrifluoroborate was reacted with 4-bromoanisole, 4-methoxyphenyltriflate, and 4-iodoanisole, 45% (isolated), 12% (by GC analysis), and no product was observed, respectively, after 3 days (Table 4, entry 1).[45] The reaction of 3,4-dioxymethylenephenyl bromide produced a complex mixture consisting of starting bromide, dehalogenated and deboronated byproducts, homocoupling of the bromide substrate, and the desired product. Because of this mixture, the purification process was very difficult, and finally the mixture was simply analyzed by GC and GC−MS, which indicated ca. 25% of product formation (entry 3). Similarly, the reaction involving 4-bromophenol produced only traces of desired product (below 5% by GC analysis) (entry 4), and 4-bromo-*N*,*N*-dimethylaniline afforded none of the coupled product (entry 5).

On the other hand, the reactions of 3-bromoanisole and 2-bromotoluene reached completion after 18 h, providing good yields of products (entries 2 and 6). Even the reaction of the more sterically hindered 2-bromomesitylene achieved a good conversion into product after 1 day (entry 7).

In summary, we have synthesized new potassium alkyltrifluoroborates from potassium methyltrifluoroborate to alkyltrifluoroborates with different heteroatoms present in the alkyl chain. All of them were easily synthesized through different procedures as white solids, easy to handle and stable in the air. Furthermore, we have tested their reactivity in the *B*-alkyl Suzuki−Miyaura cross-coupling reaction. One of the most remarkable facts is their uniform behavior. Thus, under the same catalyst system potassium alkyltrifluoroborates undergo the cross-coupling reaction satisfactorily. In addition, the 3-heteropropyl trifluoroborates allowed the cross-coupling of a substitution pattern that otherwise might not be possible with other borane derivatives.

TABLE 4. Cross-Coupling Reaction of Potassium 2-Phenylethyltrifluoroborate 3f



entry	ArBr or ArOTf	product	% isolated yield[a,b,c]
1			**7a**, 12 (X = OTf)[d] 45 (X = Br) — (X = I)
2			**7b**, 86
3			**7c**, 25[d]
4			**7d**, traces
5			**7e**, —
6			**7f**, 82
7			**7g**, 68

[a] Isolated yield. [b] Different proportions of homocoupling of the electrophile, as well as protodeboronated and protodehalogenated byproducts, were observed. [c] The reaction times were not optimized. [d] Detected by GC and GC−MS analysis.

Experimental Section

Potassium Methyltrifluoroborate (1). To a mixture of KHF_2 (19.0 g, 243 mmol, 6 equiv) in 200 mL of acetonitrile was added trimethylboroxine (5.14 g, 41 mmol, 3 equiv) at room temperature, and the mixture was then cooled to 0 °C and stirred for 30 min. Then H_2O (4.5 mL) was added. After 3 h of stirring the solvent was evaporated, and the resulting solid was thoroughly dried under vacuum. The resulting solids were triturated in acetone/methanol 1:1 (100 mL), filtered, and washed once with the same mixture of solvents (100 mL) and once with acetone/methanol 1:2 (100 mL). The remaining insoluble white solid was dried on a high-vacuum Schlenk line to give 12.01 g (80% yield) of the potassium methyltrifluoroborate as a white powder, mp 282 °C: ^{1}H NMR (D_2O) δ −0.15 (s); ^{13}C NMR (D_2O) δ 1.40 to −1.14 (br s); ^{19}F NMR (D_2O) δ −132.3 (q, J = 64.3 Hz); ^{11}B NMR (D_2O) δ 7.25 (q, J = 64.4 Hz). Anal. Calcd for CH_3BF_3K: C, 9.85; H, 2.48; Found: C, 9.81; H, 2.50.

Potassium Trimethylsilylmethyltrifluoroborate (2). To an ether solution (0.5 M) of trimethylsilylmethyl boronic acid (900 mg, 6.7 mmol, 1 equiv) was added KHF_2 (1.50 g, 20.3 mmol, 3 equiv) followed by 3 mL of H_2O at room temperature. The resulting mixture was stirred for 1 h. The reaction mixture was extracted several times with acetone, and the combined extracts were concentrated and then held under high vacuum

(43) $PdCl_2(dppf)$ uncomplexed with CH_2Cl_2 was used. For the preparation of this precatalyst, see: Hayashi, T.; Konishi, M. Kobori, Y.; Kumada, M.; Higuchi, T. Hirotsu, K. *J. Am. Chem. Soc.* **1984**, *106*, 158−163.

(44) Spectroscopic and physical data of **7a**, **7e** (see ref 16), and **7f** were identical to those described in the literature: Savin, V. I. J. *Org. Chem. USSR (Engl. Transl.)* **1992**, *28*, 35−41.

(45) To fully assess the reactivity of the iodoaryls, 4′-iodoacetophenone was also tested under similar conditions. No product was observed after 3 days, with a high proportion of acetophenone formation, showing the lack of reactivity in the transmetalation step, and subsequent protodehalogenation after prolonged heating.

for 30 min. The resulting white solid was purified by dissolution in acetone and precipitation with Et_2O to give 945 mg of a white solid, 72% yield: ^{1}H NMR (acetone-d_6) δ −0.09 (s, 9H), −0.5 (m, 2H); ^{13}C NMR (acetone-d_6) δ 6.27 (m), 1.3; ^{19}F NMR (DMSO-d_6) δ −132.0 (m); ^{11}B NMR (DMSO-d_6) δ 7.9 (m).

Potassium 3-Chloropropyltrifluoroborate (3a). To a mixture of allyl chloride (1.4 g, 16 mmol) and $HSiEt_3$ (2.0 g, 17 mmol) was added a solution of BCl_3 (1 M in hexane, 18 mL, 18 mmol) at −78 °C under an argon atmosphere. The resulting suspension was stirred at this temperature for 30 min, after which it was allowed to warm to room temperature for 1 h. The mixture was cooled to 0 °C, and water (30 mL) and ether (30 mL) were slowly added. The suspension was stirred for 30 min and then extracted with ether. The combined extracts were dried over $MgSO_4$ and filtered. After removal of the solvent the white solid was purified by crystallization, affording 1.4 g of the boronic acid. A part of the resulting boronic acid (850 mg, 7 mmol) was dissolved in ether (20 mL), and KHF_2 (2.30 g, 29.4 mmol) was added followed by the addition of water (1 mL) over 1 h. The mixture was extracted with acetone and the combined extracts were concentrated and then held under high vacuum for 30 min. The resulting white solid was purified by dissolving in hot acetone and precipitating with Et_2O, providing a white solid (1.03 g, 5.6 mmol, 80% yield), mp >290 °C: ^{1}H NMR (DMSO-d_6) δ 3.48 (t, J = 7.7 Hz, 2H), 1.57 (quint, J = 7.7 Hz, 2H), 0.01 (m, 2H); ^{13}C NMR (DMSO-d_6) δ 49.8, 30.9, 17.4 (m); ^{19}F NMR (DMSO-d_6) δ −137.7 (m); ^{11}B NMR (DMSO-d_6) δ 5.22.

Potassium 3-Phenylsulfenylpropyltrifluoroborate (3b). To a solution of allyl phenyl sulfide (1.0 g, 6.6 mmol, 1 equiv) in CH_2Cl_2 (25 mL) was added a solution of $HBBr_2{\cdot}SMe_2$ (1 M in CH_2Cl_2, 13.3 mL, 13.3 mmol, 2 equiv). The resulting suspension was stirred at reflux for 24 h and then allowed to cool to room temperature. The mixture was cooled further to 0 °C, and water and ether were slowly added. The suspension was stirred for 30 min, extracted with ether, dried over $MgSO_4$, and filtered. After removal of the solvent the white solid was purified by crystallization in ether/hexane, providing 1.0 g of the boronic acid (80% yield): ^{1}H NMR ($CDCl_3$) δ 7.32−7.23 (m, 4H), 7.11 (t, J = 1.2 Hz, 1H), 2.97−2.92 (m, 2H), 1.82−1.74 (m, 2H), 1.02−0.0 (m, 2H); ^{11}B NMR ($CDCl_3$) δ 33.5 (m). A part (770 mg, 3.9 mmol) of the resulting boronic acid derivative was dissolved in ether (20 mL), and KHF_2 (915 mg, 11.7 mmol, 3 equiv) was added followed by the addition of water (1 mL) over 1 h. The mixture was extracted several times with acetone, and the combined extracts were concentrated and then held under high vacuum for 30 min. The resulting white solid was purified by dissolving in hot acetone and precipitating with ether, affording **3b** as a flaky white solid (935 mg, 93% yield), mp 289 °C: ^{1}H NMR (DMSO-d_6) δ 7.27−7.23 (m, 4H), 7.11 (t, J = 1.2 Hz, 1H), 2.83 (t, J = 7.8 Hz, 2H), 1.47−1.44 (m, 2H), 0.07−0.05 (m, 2H); ^{13}C NMR (DMSO-d_6) δ 137.7, 128.7, 127.2, 124.7, 35.4, 25.8; ^{19}F NMR (DMSO-d_6) δ −136.7; ^{11}B NMR (DMSO-d_6) δ 5.73.

General Procedure for Preparation of Potassium Alkyltrifluoroborates 3c and 3d. Potassium 3-Benzoyloxypropyltrifluoroborate (3c). To a solution of allylbenzoate (1.0 g, 6.2 mmol, 1 equiv) in CH_2Cl_2 (20 mL) in the presence of 1 mol % $Rh(PPh_3)_3Cl$ catalyst was added pinacolborane (1.0 M THF solution, 1.2 g, 9.2 mmol, 1.5 equiv) at 0 °C. The reaction mixture was allowed to warm to room temperature and was stirred for 24 h. Water was added and the mixture was extracted with ether, dried over $MgSO_4$, and filtered. After removal of the solvent, the boronic ester was purified by column chromatography (hexane/AcOEt 8/1) to provide **3c** as a colorless oil (1.5 g, 85% yield): ^{1}H NMR ($CDCl_3$) δ 8.01 (dd, J = 7.1 and 1.2 Hz, 2H), 7.49 (t, J = 6.3 Hz, 1H), 7.38 (t, J = 7.3 Hz, 2H), 4.26 (t, J = 7.2 Hz, 2H), 1.86−1.83 (m, 2H), 1.22 (s, 3H), 1.21 (s, 3H), 1.20 (s, 3H), 1.19 (s, 3H), 0.89−0.84 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 166.5, 132.6, 130.5, 129.5, 128.1, 83.0, 82.7, 66.6, 24.7, 23.2, 7.3 (m); ^{11}B NMR ($CDCl_3$) δ 35.04 (m). A part of the resulting product (1.0 g, 3.5 mmol) was dissolved in MeCN (20 mL) and KHF_2 (800 mg, 11.2 mmol, 3.1 equiv) was added at room temperature followed by the addition of water (2.5 mL) over 1 h. The mixture was extracted several times with acetone, and the extracts were combined, concentrated, and then held under high vacuum for 1 h. The resulting white solid was purified by dissolving in hot MeCN and precipitating with Et_2O, providing a white solid (700 mg, 75%), mp 183 °C: ^{1}H NMR (acetone-d_6) δ 8.02 (dd, J = 7.0 and 1.3 Hz, 2H), 7.59 (t, J = 6.2 Hz, 1H), 7.48 (t, J = 7.3 Hz, 2H), 4.23 (t, J = 7.3 Hz, 2H), 1.70 (quint, J = 7.9 Hz, 2H), 0.24 (br s, 2H); ^{13}C NMR (acetone-d_6) δ 167.0, 133.5, 132.2, 130.1, 129.3, 69.2, 25.9, 23.4; ^{19}F NMR (acetone-d_6) δ −141.8 (m); ^{11}B NMR (acetone-d_6) δ 8.35 (br s).

Potassium 3-(*p*-Tolylsulfonylamino)propyltrifluoroborate (3d). The compound was prepared following the above procedure, starting with 705 mg (3.3 mmol) of allylamine, *p*-tolylsulfonamide, pinacolborane (1.0 g, 5.6 mmol, 1.7 equiv), and 1 mol % $Rh(PPh_3)_3Cl$. The boronic ester derivative was isolated as a colorless oil (820 mg, 60%): ^{1}H NMR ($CDCl_3$) δ 7.68 (d, J = 8.1 Hz, 2H), 7.24 (d, J = 8.1 Hz, 2H), 4.88 (br t, 1H, NH), 2.88−2.84 (m, 2H), 2.37 (s, 3H), 1.54−1.51 (m, 2H), 1.21 (s, 6H), 1.18 (s, 6H), 0.69 (t, J = 6.5 Hz, 2H); ^{11}B NMR ($CDCl_3$) δ 21.9 (m). A part of the boronic ester (500 mg, 1.4 mmol, 1 equiv) was treated with 400 mg of KHF_2 (4.2 mmol, 3 equiv) following the same procedure as above. After recrystallization in $CHCl_3$ the corresponding potassium trifluoroborate **3d** was obtained as a white solid (320 mg, 75% yield), mp 120 °C: ^{1}H NMR (DMSO-d_6) δ 7.65−7.63 (AA′, 2H), 7.37−7.35 (BB′, 2H), 7.14 (br t, J = 1.1 Hz, 1H, NH), 2.58−2.55 (m, 2H), 2.37 (s, 3H), 1.23 (quint, J = 7.7 Hz, 2H), −0.16 to −0.21 (m, 2H); ^{13}C NMR (acetone-d_6) δ 143.3, 139.6, 130.2, 128.1, 47.3, 26.5, 25.3 (m), 21.4; ^{19}F NMR (acetone-d_6) δ −140.3 (br s); ^{11}B NMR (acetone-d_6) δ 8.25 (br s).

Representative Procedure for Cross-Coupling of Potassium Methyltrifluoroborate 1 and Trimethylsilylmethyltrifluoroborate 2 with Aryl Triflates or Aryl Halides (Method A). Preparation of 4-Methylacetophenone[46] (4a). To a suspension of potassium methyltrifluoroborate (**1a**) (75 mg, 0.50 mmol), Cs_2CO_3 (489 mg, 1.50 mmol), $PdCl_2(dppf){\cdot}CH_2Cl_2$[47] (36 mg, 0.05 mmol), and 4-acetylphenyltriflate (148 mg, 0.55 mmol) in THF (5 mL) was added water (0.5 mL) under an argon or nitrogen atmosphere. The reaction mixture was stirred at reflux temperature for 18 h (6−8 h for trimethylsilylmethyltrifluoroborate **2** or 3 d for alkyltrifluoroborates **3a**−**e**), then cooled to room temperature, diluted with water (10 mL), and extracted with ether. The combined organic extracts were washed with 1 N HCl (20 mL) and brine (20 mL) and then dried over magnesium sulfate. The solvent was removed in vacuo, and the crude product was purified by silica gel column chromatography (eluting with hexane/EtOAc = 8/1) to yield **4a** (92 mg, 85%): R_f = 0.47 (EtOAc/hexane = 1/8); ^{1}H NMR ($CDCl_3$) δ 7.85 (d, J = 8.1 Hz, 2H), 7.25 (d, J = 8.1 Hz, 2H), 2.57 (s, 3H), 2.41 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 197.8, 143.8, 134.7, 129.2, 128.4, 26.5, 21.6.

Acknowledgment. We thank Johnson & Johnson, Merck Research Laboratories, Aldrich Chemical Co., Array BioPharma, and Johnson Matthey for their generous support, and Dr. Takatoshi Ito for his preliminary work on this project.

Supporting Information Available: Experimental details and structural data (NMR spectra) for all compounds described within the text. This material is available free of charge via the Internet at http://pubs.acs.org.

JO0343331

(46) Spectroscopic and physical data of **4a**−**f**, **4h**, and **2j**−**k** were identical to those of authentic samples available from Aldrich.

(47) In the case of potassium alkyltrifluoroborates **3a**−**e,** $PdCl_2(dppf)$ uncomplexed with CH_2Cl_2 was used. See ref 43.