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Synthesis of Unsaturated Organotrifluoroborates via Wittig and Horner−Wadsworth−Emmons Olefination

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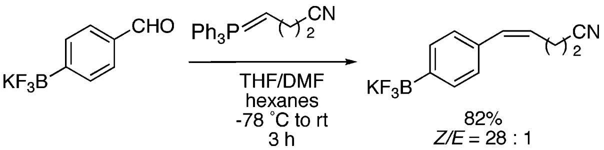

The stereoselective synthesis of unsaturated organotrifluoroborates by using the Wittig and Horner−Wadsworth−Emmons olefination is described. These reactions were general for both alkyl- and aryltrifluoroborates. The synthesis of di- and trisubstituted olefins was achieved by using formyl- and acetyl-substituted organotrifluoroborates. The products were isolated in moderate to excellent yield. The Wittig reaction with nonstabilized ylides was performed under salt free conditions in most cases to obtain the *Z*-isomer. The *E*-isomer was accessed by using preformed stabilized ylides. The Horner−Wadsworth−Emmons reaction also gave the *E*-isomer as expected.

Introduction

Organoboron compounds are becoming increasingly important components of transition metal catalyzed organic transformations, but the synthesis of functionalized organoboron compounds can be challenging because of the incompatibility of the methods employed to generate the organoboron moiety with other substituents. For example, although catalyzed and uncatalyzed hydroboration reactions[1,2] as well as the transmetalation of organolithium and Grignard reagents[3] are often used to prepare organoboron derivatives, competitive side reactions with existing, sensitive functionalities in the substrate can limit the use of these methods. These limitations make the installation of added functionality to an existing organoboron compound attractive, but this approach is rarely feasible and has not often been employed for obvious reasons. Thus, boronic acids are relatively strong Bronsted acids, while organoboranes and boronate esters are Lewis acidic. All of these classes of organoborons are thus susceptible to reaction with nucleophiles and bases that are often required for carbon−carbon bond-forming reactions and functional group transformations.

Wittig[4] and Horner-Wadsworth−Emmons[4a,d,5] (HWE) reactions have been widely used in synthesis as a means of elaborating the carbon skeleton and introducing further functionality into organic substrates. The generality and high stereoselectivity of these reactions constitute two desirable features offered by these protocols. Additionally, the double bond geometry can be predicted and controlled by choosing the appropriate reagents and reaction conditions. These characteristics make these reactions attractive for the assembly of olefinated organoboron compounds, reagents that could subsequently be utilized in further carbon−carbon bond forming reactions via transition metal catalyzed reactions (e.g., Suzuki−Miyaura coupling).[6]

To the best of our knowledge, no examples of Wittig or HWE reactions have been reported with use of suitably functionalized boronic acid derivatives, undoubtedly because of the presence

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of the acidic protons in these species. On the other hand, the Wittig and HWE reactions using aromatic boronate esters with stabilized ylides and phosphonates have been reported to a very limited extent,[7,8] but these transformations suffer because of the presence of the pinacol unit, which adds to the expense and detracts from the atom economy of the overall process.

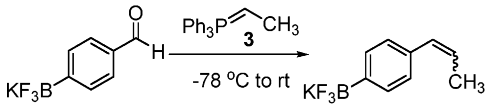
The current contribution focuses on the employment of the Wittig and HWE reactions to functionalize the more robust potassium organotrifluoroborates. Potassium organotrifluoroborates are unique and versatile organoboron compounds.[9] They can be easily prepared by the addition of inexpensive KHF_2 to a variety of organoboron intermediates.[10] These organoboron substrates are crystalline powders stable to both air and moisture. The utility of potassium organotrifluoroborates has been demonstrated by their application in Suzuki−Miyaura-type coupling reactions,[9] rhodium-catalyzed 1,4 additions,[11] and allylation reactions,[12] making them highly attractive synthetic reagents. The interest in the synthesis of unsaturated potassium organotrifluoroborates, in particular, has been reinforced upon the development of methods for epoxidation[13] and dihydroxylation[14] of these substrates while preserving the trifluoroborate unit.

Results and Discussion

Initial studies were directed toward the Wittig reaction of both formyl- and acetyl-substituted organotrifluoroborates with nonstabilized ylide reagents. The anionic character of this reaction provided information about the tolerance of the trifluoroborate to the reaction conditions. The goal was to develop a general method that would allow use of both aryltrifluoroborates and alkyltrifluoroborates.

The reaction between 4-formylphenyltrifluoroborate (**1a**) and an ethyltriphenylphosphonium bromide-derived ylide (**3**) was chosen to develop the method. Organotrifluoroborate **1a** was prepared by adding KHF_2 to the corresponding boronic acid.[10] Because the conditions to generate the ylide were well-known, attention was directed toward other aspects of the reaction. This included the ability of the reaction to reach completion and the ease of isolation of the product. To have complete conversion of the starting material was important not only to demonstrate the efficiency of the process, but also because the separation of product and starting trifluoroborate proved quite difficult.

TABLE 1. Optimization of Wittig Reaction Conditions



1a **2**

entry	ylide (equiv)	solvent	yield[a] (%)	*Z*:*E*[b]
1	1.0	THF/DMF	27	1.5:1
2	1.1	CH_3CN/THF	0	
3	1.1	DMF	34	2:1
4	1.5	DMF	72	4:1

[a] Isolated yields. [b] Based on ^1H NMR.

Traditionally, the ylide is generated by using NaHMDS in THF, which provides salt-free conditions and higher *Z*-selectivities than the corresponding lithium bases.[4a,15] However, most potassium organotrifluoroborates have poor solubility in THF. After testing the solubility of formyltrifluoroborate **1a** in various solvents amenable to the Wittig reaction, the highest concentration was achieved with DMF.

The Wittig reaction was initially performed with standard conditions: a solution of the aldehyde in a mixture of THF and DMF was added to a solution of the in situ generated ylide, followed by an aqueous workup. As shown in Table 1 entry 1, the product was isolated in poor yield. This result was attributed to the high solubility of the product in DMF. A mixture of CH_3CN/THF was then used (entry 2), but the poor solubility of **1a** in these solvents led to no reaction. The first reaction conditions were then reevaluated. Analysis of the reaction by ^1H NMR revealed that the reaction had reached completion. Therefore, the isolation of the organotrifluoroborate needed to be improved. The aqueous workup combined with the attempt to precipitate the organotrifluoroborate from the organic solution was perceived to be the major part of the difficulty. Having these factors in mind, the reaction was repeated with only DMF to dissolve the organotrifluoroborate (entry 3). Additionally, instead of an aqueous workup, the salts (NaBr) were removed by filtration and the filtrate was concentrated in vacuo. The residue was washed with CH_2Cl_2, which dissolved the organic impurities including triphenylphosphine oxide, but not the organotrifluoroborate. The trifluoroborate remained as a precipitate that could be collected and purified by recrystallization. These modifications led to a small improvement in the isolated yield. The filtration to remove NaBr was considered to be a second impediment to success, because some of the product was filtered off as well. Inorganic salts produced in the formation of ylides have previously been removed by filtration prior to reaction with the carbonyl.[4a,16] To simplify the technique further, a stock solution of the ylide was prepared, the salt formed in the ylide was allowed to settle, and the filtration step was eliminated by siphoning off the solution above the precipitate. These salt-free conditions and isolation techniques gave the final product in 72% yield after recrystallization (entry 4). The preservation of the trifluoroborate unit was demonstrated by using ^{11}B and ^{19}F NMR.

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(9) Reviews: (a) Darses, S.; Genêt, J.-P. *Eur. J. Org. Chem.* **2003**, 4313. (b) Molander, G. A.; Figueroa, R. *Aldrichim. Acta* **2005**, *38*, 49.

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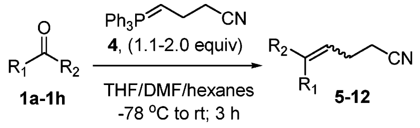
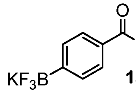
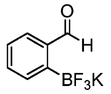
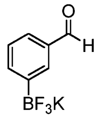
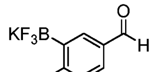
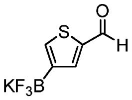
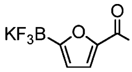
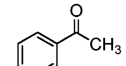
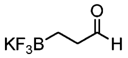
(16) Anderson, R. J.; Henrick, C. A. *J. Am. Chem. Soc.* **1975**, *97*, 4327.

TABLE 2. Wittig Reaction with Various Potassium Organotrifluoroborates



entry	substrate	% yield[a]	Z:E[c]
1	 **1a**	82	28:1
2	 **1b**	90	4.2:1
3	 **1c**	80	27:1
4	 **1d**	79	35:1
5	 **1e**	75	35:1
6	 **1f**	78	11:1
7	 **1g**	69[b]	15:1
8	 **1h**	67	(20:1)[d]

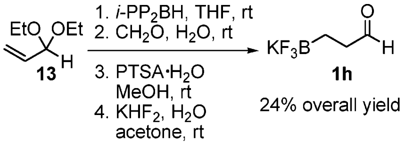
[a] Isolated yields. [b] Contaminated with 3.2% of the starting trifluoroborate. [c] Based on ^{1}H NMR. [d] Based on the ^{1}H NMR detection limit.

The optimized reaction and isolation conditions were then utilized to study the substrate scope (Table 2). The use of a functionalized ylide in the studies was attractive as a means to increase molecular complexity. Consequently, 3-cyanopropyltriphenylphosphonium bromide[17] was used to prepare the nitrile-containing ylide **4**, and this ylide was employed as a standard partner with various organotrifluoroborates.

The positional effect of the organotrifluoroborate unit in the aromatic ring relative to the reactive formyl group was first studied. Formylaryltrifluoroborates **1a**, **1b**, and **1c** were allowed to react with ylide **4** (entries 1, 2, and 3). Each reaction proceeded in excellent yield. Isolation of the product from the para- and meta-substituted organotrifluoroborates with almost the same stereoselectivity demonstrated that there is no difference in the electronic effect of the trifluoroborate at these positions, and that the reduction in selectivity of the ortho-substituted trifluoroborate **1b** is therefore due to steric effects ($A^{1,3}$-strain). The Wittig reaction of the more substituted formylaryltrifluoroborate **1d** was also very selective and high yielding. Application of the developed conditions was extended to heteroaryltrifluoroborates **1e** and **1f** (entries 5 and 6). The corresponding unsaturated organotrifluoroborates were isolated in good yield with high Z-selectivity.

The Wittig reaction of ketones is more difficult because of the decrease in reactivity of the carbonyl group. These transformations required harsher reaction conditions as well as longer reaction times.[18] However, the use of ketones is relevant for the introduction of a higher degree of substitution in the double bond. Therefore, it was important to demonstrate that potassium organotrifluoroborates with trisubstituted olefins could be prepared by using the corresponding ketones. Indeed, the reaction of potassium 4-acetylphenyltrifluoroborate (**1g**)[19] gave the olefination product in moderate yield and good selectivity with use of the same reaction conditions as those reported for the formyl substrates.

The Wittig reaction of alkyl aldehydes with nonstabilized ylides was subsequently investigated. These reactions are usually very efficient and highly selective for the generation of the Z-isomer because of the increase in reactivity as compared with aromatic aldehydes. The synthesis of the formylalkyltrifluoroborate **1h** was achieved by the hydroboration of the commercially available acrolein diethyl acetal (**13**), using the Snieckus reagent,[20] followed by deprotection and further treatment of the intermediate with KHF_2 (eq 1). The reaction between alkyltrifluoroborate **1h** and the nonstabilized ylide **4** proceeded as expected (entry 8).



(1)

The Wittig reactions with ylide **4** containing a nitrile group demonstrated the efficient use of functionalized ylides. In subsequent studies, further functional group compatibility was investigated (Table 3). Thus, ylide **14** was reacted with **1a** to afford the unsaturated organotrifluoroborate with an acetal functionality (entry 1). The lower Z/E selectivity observed in this reaction was not surprising and can be attributed to the known effect of having an oxide functionality in the ylide.[21] The preparation of the unsaturated organotrifluoroborate **18** containing an amino group surprisingly proved to be more difficult (entry 2). When NaHMDS was used to generate the ylide **15** and only 1 equiv of the ylide was used, the reaction did not reach completion. After surveying the amount of ylide required, it was found that 2 equiv were needed. However, the organotrifluoroborate isolated was contaminated with triphenylphosphine oxide. The problems in the isolation of **18** were attributed to the significant amount of byproducts in the reaction. These results led to the use of n-BuLi as the base to generate ylide **15**, thus eliminating the amine byproduct. In this manner, the Wittig reaction was accomplished with only 1.1 equiv of the ylide, and the product was isolated in 82% yield. The lower and reverse selectivity of the reaction can be attributed to two factors: the reaction is no longer under salt-free conditions (the

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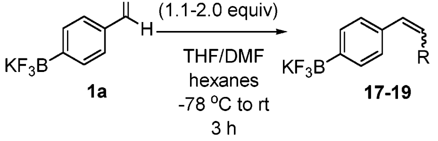
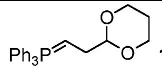
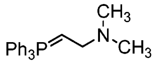
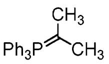
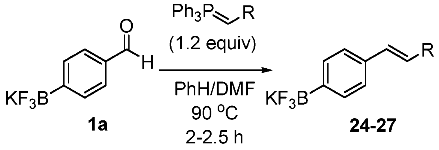
TABLE 3. Wittig Reaction with Various Unstabilized Ylides

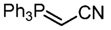
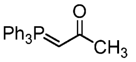
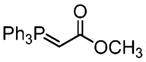
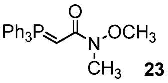


entry	ylide[a]	% yield[b]	Z:E[c]
1	 **14**	65	4:1
2	 **15**	82	1:4.6
3	 **16**	84	*N*/*A*

[a] **14** and **16** were generated with NaHMDS. **15** was generated with *n*-BuLi. [b] Isolated yield. [c] Based on ^{1}H NMR.

TABLE 4. Wittig Reaction with Various Stabilized Ylides



entry	ylide	% yield[a]	Z:E[d]
1	 **20**	92	1:24
2	 **21**	77	1:65
3	 **22**	78[b]	1:39
4	 **23**	82[c]	1:76

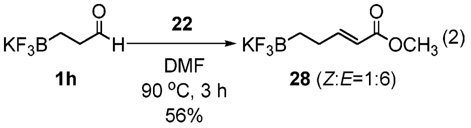
[a] Isolated yields. [b] Reaction time was 20 h. [c] Contaminated with 1% of starting trifluoroborate. DMF only as solvent. [d] Based on ^{1}H NMR.

reaction contained soluble lithium salts)[4] and the possible participation of the amino group.[20] The synthesis of trisubstituted organotrifluoroborates can be efficiently accomplished by using branched ylides such as **16**, whereupon the product was isolated in 84% yield (entry 3).

The success of the Wittig reaction of formyl- and acetyl-substititued organotrifluoroborates with nonstabilized ylides provided a motivation to explore the reaction with stabilized ylides. Carbonyl-stabilized ylides have been recognized as valuable synthetic tools to access *E*-olefins with high selectivity.[4] The reaction conditions that are often utilized employ preformed ylides or in situ generation of the ylide with mild bases. Considering the initial isolation problems observed in the reaction with nonstabilized ylides, the use of preformed stabilized ylides was more practical. In this way, the removal of inorganic or organic salts was eliminated, and furthermore, some of the preformed stabilized ylides are commercially available. Toluene and benzene are commonly used in these reactions to allow higher reaction temperatures. Once again, DMF was also used as a cosolvent to ensure the solubility of the starting trifluoroborates. The combination of benzene and DMF in a 1:1 ratio at 90 °C with a slight excess of the preformed stabilized ylides proved to be excellent reaction conditions (Table 4). Isolation of the products was then further simplified. The reaction mixtures were concentrated and washed with CH_2Cl_2 to give the product as a pure, insoluble solid that was separated by filtration (recrystallization was not needed).

Potassium 4-formylphenyltrifluoroborate (**1a**) was again used to evaluate different stabilized ylides under the indicated reaction conditions. The synthesis of α,*β*-unsaturated potassium phenyltrifluoroborates bearing a nitrile, ketone, ester, and Weinreb amide functional group was conducted in moderate to excellent yields by using ylides **20**,[22] **21**, **22**, and **23**, respectively. All the reactions proceeded smoothly in a short period of time except for the reaction with ylide **21**, which required 20 h. The longer reaction time required by ylide **21** has been attributed to a lower reactivity that results from higher stabilization of the nucleophile.[4b] Additionally, the use of benzene is not required in the reaction. This was demonstrated in the synthesis of organotrifluoroborate **27**, wherein DMF was used as the only solvent. These results demonstrate the synthetic merit of this transformation to introduce valuable functionalities in the organotrifluoroborates. It also shows the stability of the trifluoroborate unit under these mildly anionic conditions.

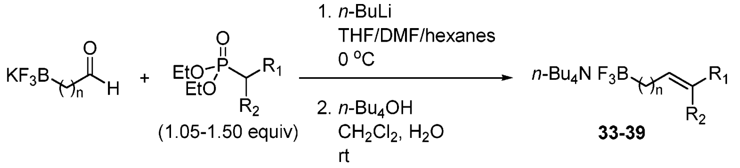
The method was also extended to the use of formyl-substituted alkyltrifluoroborates as shown in eq 2. Alkyltrifluoroborate **1h** was reacted with methoxycarbonylmethylenephosphorane (**22**) to yield the product in 56% yield. The observed yield and stereoselectivity were lower than those for the aryltrifluoroborates. The reduced selectivity was not surprising because of the higher reactivity of alkanals. In this case, the trifluoroborate unit showed some degradation as demonstrated by the presence of inorganic salts in the ^{19}F NMR of the product. Nevertheless, these results demonstrated the generality of the reaction for both the organotrifluoroborate and the ylide.

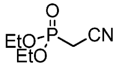
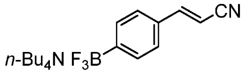
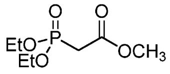
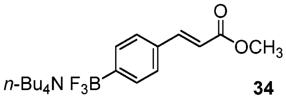
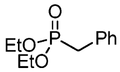
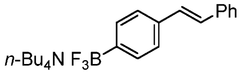
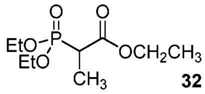
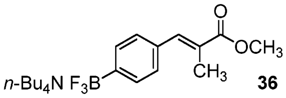
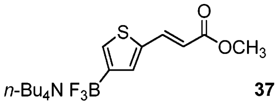
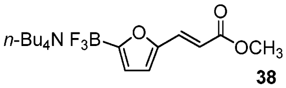
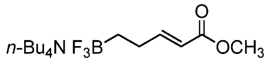


After completing the Wittig reactions, studies were initiated toward the application of the Horner−Wadsworth−Emmons olefination of appropriately functionalized potassium organotrifluoroborates. It was important to demonstrate that either of the two olefination tools could be utilized to synthesize unsaturated organotrifluoroborates, and to demonstrate the use of both alkyl- and aryltrifluoroborates in the HWE reaction. This reaction offers the advantage that higher *E*-selectivity can be achieved in many cases compared to the Wittig reaction. The solubility of the byproducts of the HWE reaction in water was anticipated to facilitate isolation and purification of the elaborated trifluoroborates.

The previous studies on the Wittig reaction provided a basic set of information useful in the exploration of the HWE olefination. Thus, the starting trifluoroborate would be added in DMF to the phosphonate carbanion solution. The phosphonate carbanion was generated in situ following standard conditions. Preliminary studies with aldehyde **1a** and phosphonates **29** and **30** were helpful in the development of isolation conditions. In both cases, partial precipitation of the product was observed. Unfortunately, the precipitated products were contaminated with

TABLE 5. HWE Reaction with Various Organotrifluoroborates and Phosphonates



entry	aldehyde	phosphonate	product	% yield[a]	*Z*:*E*[c]
1	**1a**	 **29**	 **33**	70[b]	1:9
2	**1a**	 **30**	 **34**	91	1:125
3	**1a**	 **31**	 **35**	75	(1:20)[d]
4	**1a**	 **32**	 **36**	65	(1:20)
5	**1e**	**30**	 **37**	73[b]	1:200
6	**1f**	**30**	 **38**	85[b]	1:37
7	**1h**	**30**	 **39**	41[b]	1:40

[a] Isolated yields. [b] Contaminated with 4−6% of phosphonate species. [c] Based on ^{1}H NMR. [d] Based on the ^{1}H NMR detection limit.

the phosphate byproduct [(EtO$_2$)P═O(OLi)]. Nevertheless, advantage was taken of this phenomenon. Further precipitation of the organotrifluoroborate could be induced to separate the solid mixture from the excess phosphonate. Isolation of the organotrifluoroborate could then be achieved by taking advantage of the water solubility of the phosphate combined with the Batey and Quach cation exchange reaction to generate tetrabutylammonium organotrifluoroborates.[23] By using this strategy, the tetrabutylammonium salts migrated into the organic phase, and the phosphate byproduct remained in the aqueous phase.

Once the reaction and isolation conditions were optimized, the scope of the HWE olefination with use of aryltrifluoroborates was studied (Table 5). The conditions developed were general for various phosphonates (entries 1−4). The lower selectivity observed with phosphonate **29** can be attributed to the higher reactivity of the anion as compared with the more stabilized phosphonate **30** combined with the smaller steric influence of the cyano group. The synthesis of the styrylphenyltrifluoroborate **35** proceeded in good yield by using the semistabilized carbanion from phosphonate **31**. The use of the branched phosphonate **32** was important from the point of view of introducing more substitution in the olefin. Indeed, the trisubstituted organotrifluoroborate **36** was prepared in 65% yield. This yield was achieved after removal of the excess phosphonate **32** by extraction with an aqueous solution of KOH. Some of the products trapped a small percent of the phosphonates, but the remains of these starting materials could be easily removed by this simple extraction protocol.

Formylheteroaryltrifluoroborates could also be used to synthesize the corresponding α,*β*-unsaturated compounds (entries 5 and 6). The use of formylalkyltrifluoroborate **1h** proceeded with high selectivity but in lower yield (entry 7).

Conclusion

Although organoborons (particularly boronic acids and boronate esters) are playing an increasing role in the synthesis of organic molecules via transition metal catalyzed processes, in general these reagents are synthesized in one synthetic step and transformed immediately without further functional group elaboration. This is due in large part to the Bronsted and Lewis acidic properties of these materials. Because of this, practitioners

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(22) Prepared according to a procedure reported by: Mauduit, M.; Kouklovsky, C.; Langlois, Y. *Tetrahedron Lett.* **1998**, *39*, 6857.

(23) Batey, R. A.; Quach, T. D. *Tetrahedron Lett.* **2001**, *42,* 9099.

are severely limited in their approach to complex molecule synthesis by the chemical characteristics of the reagents themselves.

The tetracoordinate nature of organotrifluoroborates shields them from reactions with Lewis bases and nucleophiles under normal reaction conditions. Remote functionality can thus be transformed under anionic conditions, leaving the valuable carbon−boron bond intact for eventual coupling processes. Consequently, the sensitivity of the boron moiety itself is largely removed from consideration in synthetic schemes, and potential retrosynthetic analyses to target molecules can be greatly expanded.

In the current demonstration of this approach, the stereoselective synthesis of unsaturated potassium organotrifluoroborates via the Wittig and Horner−Wadsworth−Emmons reaction was accomplished in moderate to excellent yields. The established reaction conditions allow the isolation of the products as stable solids with high purity. Thus, relatively simple organoboron substructures can be elaborated by olefination, increasing molecular complexity while retaining the valuable carbon−boron bond for subsequent transformations.

Experimental Section

General Procedure for the Wittig Reaction with Nonstabilized Ylides: Preparation of (*Z*)-Potassium 4-(4-Cyanobut-1-enyl)-phenyltrifluoroborate (5). A mixture of 3-cyanopropyltriphenylphosphonium bromide[17] (821 mg, 2.00 mmol) in THF (2.0 mL) was cooled to 0 °C (ice−water bath). To the slurry was added 1.0 M NaHMDS in THF (2.0 mL, 2.0 mmol). The resulting orange to red solution was stirred for 30 min. The ice bath was removed and the stirring was stopped. The mixture was allowed to settle (~1 h) until the precipitate (NaBr) completely separated from the solution. To a mixture of potassium 4-formylphenyltrifluoroborate (**1a**) (212 mg, 1.0 mmol) in DMF (1.0 mL) was added the ylide solution (2.2 mL, 1.1 mmol) via syringe at −78 °C. (Note: If the solution freezes the flask can be removed from the bath until everything goes in solution, and then returned to the bath.) After the solution was stirred for 1 h, the ice bath was removed and stirring was continued for another 2 h. The mixture was concentrated under high vacuum overnight until almost all the DMF and HMDS was removed. To the residue was added CH_2Cl_2, and the mixture was stirred until there was an evident separation of a solid. The solid was collected by suction filtration and washed with three small portions of CH_2Cl_2 to afford the crude product as a brown solid. The solid was stirred in a solution of 10% MeOH in acetone. Then, Et_2O was added until no more precipitation was observed. The precipitate was collected, washed with small portions of Et_2O, and dried under high vacuum to yield 215 mg (82%) of a yellow solid. Mp 186−188 °C; IR (KBr) ν_{max} 3062 (=C−H), 2252 (C≡N), 1606 (C=C) cm^{-1}; ^1H NMR (500 MHz, DMSO-d_6) δ 7.33 (d, J = 7.6 Hz, 2H), 7.04 (d, J = 7.5 Hz, 2H), 6.48 (d, J = 11.5 Hz, 1H), 5.50 (dt, J = 11.5, 6.5 Hz, 1H), 2.64−2.59 (m, 4H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 133.0, 131.9 (2C), 131.3, 126.64, 126.62 (2C), 120.4, 24.2, 16.7; ^{19}F NMR (470 MHz, DMSO-d_6) δ −139.6; ^{11}B NMR (128 MHz, DMSO-d_6) δ 2.20; HRMS (*m*/*z*) $[M - K]^-$ calcd for $C_{11}H_{10}BF_3N$ 224.0858, found 224.0853. The *Z*/*E* ratio was 28:1 based on the integration of peaks at 5.50 and 6.12 ppm, respectively.

Anal. Calcd for $C_{11}H_{10}BF_3KN$: C, 50.21; H, 3.83. Found: C, 49.87; H, 3.99.

General Procedure for the Wittig Reaction with Stabilized Ylides: Preparation of (*E*)-Potassium 4-(2-(Methoxycarbonyl)-vinyl)phenyltrifluoroborate (26). A mixture of potassium 4-formylphenyltrifluoroborate (**1a**) (212 mg, 1.0 mmol), methoxycarbonylmethylenetriphenylphosphorane (**22**) (368 mg, 1.1 mmol), DMF (1.0 mL), and benzene (1.0 mL) was heated to 90 °C (oil bath temperature) for 2 h.[24] The reaction mixture was concentrated overnight under high vacuum.[25] CH_2Cl_2 was added to the resulting solid mixture and the slurry was stirred for about 3 min. The solids were collected by filtration, washed with three small portions of CH_2Cl_2, and dried under high vacuum to yield 210.4 mg (78%) of a white solid. Mp >220 °C; IR (KBr) ν_{max} 1712 (C=O), 1640 (C=C), 1216 (C−O) cm^{-1}; ^1H NMR (500 MHz, DMSO-d_6) δ 7.59 (d, J = 15.9 Hz, 1H), 7.43 (d, J = 6.9 Hz, 2H), 7.39 (d, J = 6.8 Hz, 2H), 6.49 (d, J = 15.9 Hz, 1H), 3.70 (s, 3H); ^{13}C NMR (125 MHz, DMSO-d_6) δ 167.0, 146.0, 131.9 (2C), 130.7, 126.6 (2C), 115.1, 51.3; ^{19}F NMR (470 MHz, DMSO-d_6) δ −140.1; ^{11}B NMR (128 MHz, DMSO-d_6) δ 2.42; HRMS (*m*/*z*) $[M - K]^-$ calcd for $C_{10}H_9BF_3O_2$ 229.0648, found 229.0644. The *Z*/*E* ratio was 1:39 based on the integration of peaks at 5.85 and 6.49 ppm, respectively.

General Procedure for the Horner−Wadsworth−Emmons Reaction: Preparation of (*E*)-Tetrabutylammonium 4-(2-Cyanovinyl)phenyltrifluoroborate (33). The reaction was performed under a N_2 atmosphere in a two-necked round-bottomed flask. The cation exchange was performed in an open atmosphere in a round-bottom flask. To a solution of diethyl cyanomethylphosphonate (0.20 mL, 213 mg, 1.2 mmol) in THF (1.9 mL) was added 1.6 M *n*-BuLi (0.75 mL, 1.2 mmol) in hexanes at 0 °C (ice−water bath). The resulting solution was stirred for 0.5 h. Then, a solution of potassium 4-formylphenyltrifluoroboratae (**1a**) in DMF (1.0 mL) was added via syringe. The solution was kept for 1.5 h at 0 °C.[26] The ice bath was removed and the mixture was stirred for another 2 h. To the mixture was added hexanes and Et_2O in an alternate fashion until no more precipitation was observed. The solid was washed with two small portions of both hexanes and Et_2O. To a mixture of the solid in H_2O (0.4 mL) and CH_2Cl_2 (3.0 mL) was added a solution of 40 wt % *n*-Bu_4NOH (0.62 mL, 1.0 mmol) in H_2O. The biphasic solution was stirred for 0.5 h. The layers were separated. The aqueous layer was extracted with two small portions of CH_2Cl_2. The combined organic layers were washed with two small portions of H_2O, dried ($MgSO_4$), and concentrated under high vacuum to yield 305 mg (70%) of a yellow solid. Mp 95−96 °C; IR (CH_2Cl_2) ν_{max} 2213 (C≡N), 1614 (C=C) cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.65 (d, J = 7.7 Hz, 2H), 7.36 (d, J = 16.6 Hz, 1H), 7.30 (d, J = 7.6 Hz, 2H), 5.80 (d, J = 16.6 Hz, 1H), 3.07−3.00 (m, 8H), 1.53−1.46 (m, 8H), 1.35 (sextet, J = 7.3 Hz, 8H), 0.95 (t, J = 7.3 Hz, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 152.2, 132.4 (2C), 130.8, 125.9 (2C), 119.0, 93.1, 58.4 (4C), 23.7 (4C), 19.5 (4C), 13.5 (4C); ^{19}F NMR (470 MHz, $CDCl_3$) δ −142.6; ^{11}B NMR (128 MHz, $CDCl_3$) δ 1.69. HRMS (*m*/*z*) $[M\text{-}n\text{Bu}_4N]^-$ calcd for $C_9H_6BF_3N$ 196.0545, found 196.0547. The *Z*/*E* ratio was 1:9 based on the integration of peaks at 5.30 and 5.80 ppm, respectively.

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Supporting Information Available: Complete experimental details and copies of all NMR spectra (^1H, ^{13}C, ^{19}F, and ^{11}B). This material is available free of charge via the Internet at http://pubs.acs.org.

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[24] The reaction begins heterogeneous and becomes homogeneous as it reaches 90 °C and remains homogeneous until completion.

[25] Complete removal of DMF is required to facilitate isolation of the product. Slight heating (50 °C) can be used to facilitate DMF removal.

[26] At this stage partial precipitation of the product was observed.