DOI: 10.1002/ijch.201000051

Highly (≥98%) Selective Trisubstituted Alkene Synthesis of Wide Applicability via Fluoride-Promoted Pd-Catalyzed Cross-Coupling of Alkenylboranes

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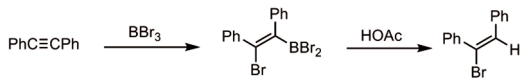
Dedicated to Prof. Morris Srebnik in recognition and appreciation of his pioneering contributions in organometallic chemistry.

Abstract: (*Z*)-β-bromo-1-propenyl(pinacol)borane (**4**), recently made available in 85% yield as a ≥98% isomerically pure compound via bromoboration of 1-propyne, has been converted to β-alkyl-, aryl-, and alkenyl-substituted (*Z*)-2-methyl-1-alkenyl(pinacol)boranes (**2a**) in ca. 75% yield based on propyne via Pd-catalyzed Negishi alkenylation with suitable organozinc bromide. The previously sluggish and modest-yielding Suzuki alkenylation of β,β-disubstituted alkenylboranes has been significantly promoted by fluorides, especially nBu$_4$NF(TBAF) or CsF, to give trisubstituted alkenes, i.e., (*Z*)-β-Me-substituted **3-i–3-xi** and (*E*)-β-Ph-substituted **2b–i** and **2b–ii**. In all cases, each alkene product was formed in a ≥98% stereoselectivity. The propyne-based protocol nicely complements the widely used Zr-catalyzed alkyne methylalumination–Pd-catalyzed alkenylation by providing a highly stereoselective(≥98%) route to (*Z*)-Me-substituted alkenes.

Keywords: alkene synthesis · bromoboration · cross-coupling · F-promoted alkenylation · (*Z*)-β-bromo-1-alkenyl(pinacol)borane

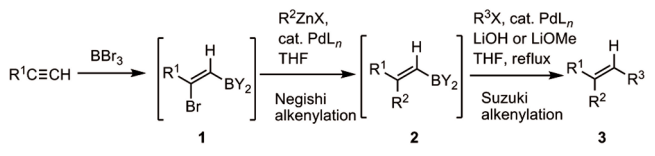
1. Introduction

Haloboration of alkynes with haloboranes, reported first by Lappert in 1964[1] (Scheme 1), is a rare alkyne halometalation which must be rendered thermodynamically favorable, in part, by virtue of boron's high electronegativity for a metal. Its kinetic facility and high stereoselectivity, often nearly 100% *syn*, make it an attractive and potentially useful tool for selective synthesis of trisubstituted alkenes.



Scheme 1.

Indeed, this was realized by Suzuki[2] in the late 1980s through development of an alkyne haloboration–Pd-catalyzed Negishi–Suzuki tandem alkenylation (Scheme 2).



R, R^1, R^2, and R^3 = carbon groups; X = halogen or R^2; Y = Br, OH, alkoxy; PdL_n = Pd catalyst

Scheme 2.

It should be noted here that, despite very high synthetic utilities of the Zr-catalyzed carboalumination, especially methylalumination (ZMA) discovered and developed by us,[3] and Normant's prototypical carbocupration[4] of alkynes, their scopes are largely limited to *syn*-alkylmetalation of alkynes. Since both halogen (X) and boryl groups (BY_2) of **1** can, in principle, be substituted with a wide variety of carbon groups by Pd-catalyzed Negishi and/or Suzuki alkenylation,[5] the protocol shown in Scheme 2 promised to provide an unprecedentedly broad-scoped and highly (≥98%) selective route to trisubstituted alkenes (**3**) via **2**. In reality, however, some critical limitations including the following have been reported: (i) The arguably single most important case of propyne haloboration was reported to be ≤90% stereoselective.[2b] (ii) Although haloboration of terminal alkynes containing aryl and other unsaturated carbon groups proceeds satisfactorily, subsequent Pd-catalyzed substitution of the β-

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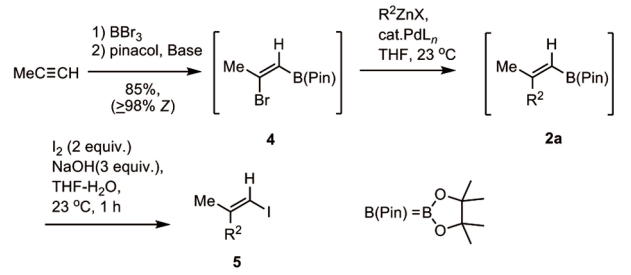
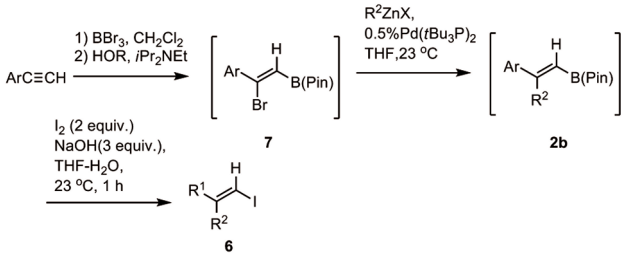
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ijch.201000051

halogen atom was plagued with unwanted dehaloboration to regenerate the original 1-alkynes.[6] (iii) As reported by Suzuki,[2a] the Suzuki alkenylation with β,β-disubstituted alkenylboranes for producing the desired trisubstituted alkenes not only required a large excess, up to 75 equivalents, of a base, such as LiOH and LiOMe, but led to modest product yields of mostly 50–70%. To cope with these difficulties and inconveniences, Wang[7] and the authors' group[8] opted for a circuitous route via borane-to-iodide conversion followed by the second Negishi alkenylation, but a more direct and satisfactory procedure was clearly desirable.

Gratifyingly, recent efforts in the authors' group have led to an excellent procedure for one-pot conversion of propyne into **4** of 98% *Z* in 85% yield and its subsequent conversion to a wide variety of **5** in good yield via Negishi alkenylation followed by iodinolysis (Scheme 3) and the corresponding procedure with arylethynes[6] (Scheme 4).



Scheme 3.



Scheme 4.

Although these procedures are highly selective and satisfactory, especially in those cases where the use of organozincs rather than the corresponding halides is distinctly more favorable, as in alkylation with alkylzincs, it was nevertheless desirable to avoid the intermediacy of alkenyl iodides **5** and **6** for the synthesis of **3**. To this end, the use of fluorides as promotors of Suzuki alkenylation of β,β-disubstituted alkenylboranes (**2**) was considered. Survey of the literature has indicated that the use of fluorides in Suzuki arylation[9] has been extensively studied, but their use in Suzuki alkenylation has been much less reported,[9a,10] despite an early pioneering work of Srebnik[10a] reporting a CsF-promoted selective Suzuki alkenylation with a β,β-disubstituted alkenylboranes in preference to a (*Z*)-α,β-disubstituted alkenylborane present in the same compound.

We herein report the development of highly (≥98%) selective and satisfactory procedure for Pd-catalyzed cross-coupling of β,β-disubstituted alkenylboranes (**2**) to give a wide range of trisubstituted alkenes (**3**) that is promoted by fluorides, such as nBu$_4$NF(TBAF) and CsF.

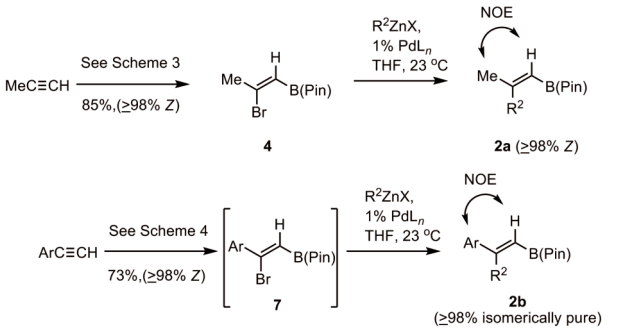
2. Results and Discussion

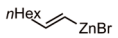
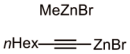
Preparation of (*Z*)-2-bromo-1-alkenyl(pinacol)boranes(1) and β,β-disubstituted -1-alkenyl(pinacol)boranes (2)

Preparation of (*Z*)-2-bromo-1-propenyl(pinacol)borane (**4**) was carried out by bromoboration of propyne with BBr_3 (1.1 equiv.) in CH_2Cl_2 at –78 to 23 °C followed by addition of pinacol (1.2 equiv., –78 to 23 °C) to give **4** as a ≥98% isomerically pure compound in 85% isolated yield (Scheme 3).[8b] Since **4** was to be used for the preparation of ten to a dozen trisubstituted alkenes, we opted for preparing isolated and pure **4** and using it for subsequent transformations. For the syntheses of arylethyne-derived trisubstituted alkenes, we opted for generating in situ (*Z*)-2-bromo-2-aryl-1-ethenyl(pinacol)boranes (**7**) and converting them into **2b** without isolation of **7** in the more limited part of this study. In both cases, those results reported earlier were closely reproduced, and those that are pertinent to this study are summarized in Table 1.

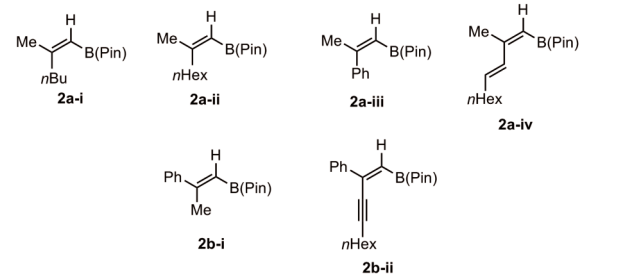
Selection of the reaction conditions was mostly based on our recent studies.[6,8] Thus, for conversion of β-bromo-1-propenyl(pinacol)boranes (**4**) to β,β-disubstituted-1- alkenyl(pinacol)boranes (**2a**), organozincs were uniformly satisfactory reagents. For alkenylation, alkenylindium and alkenylzirconium derivatives were also reasonably satisfactory.[8b] For Pd-catalyzed Negishi coupling of alkyl-substituted β-bromo-1-alkenylboranes, such as **4**, various conventional Pd catalysts, such as $Pd(PPh_3)_4$, $PdCl_2(PPh_3)_2$, and $PdCl_2$(DPEphos), were arbitrarily and successfully used. On the other hand, β-aryl-containing β-bromo-1-alkenylboranes, such as **7**, are much more readily prone to competitive β-debromoboration. To cope with this difficulty, the use of highly active catalysts, such as $Pd(tBu_3P)_2$ and PEPPSI^{TM}-IPr (**8**) (Figure 1), where PEPPSI stands for [1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene](3-chloropyridyl)palladium(II) dichloride,[11] proved to be essential.[6] Each of the products **2a** and **2b** was formed and isolated as a ≥98% isomerically pure compound. Neither ^{1}H nor ^{13}C NMR spectrum at the S/N ratio of ≥50–100 revealed any signals for isomeric products. The assigned stereochemistry is fully supported by NMR spectroscopy including NOE measurements.

Table 1. Preparation of (*Z*)-2-methyl-1-alkenyl(pinacol)boranes (**2a**) and 2-aryl-1-alkenyl(pinacol)boranes (**2b**).



entry	1-alkyne	R^2ZnX	PdL_n(mol%)	time(h)	product	overall yield from alkyne(%)
1	MeC≡CH	*n*BuZnBr	$PdCl_2(PPh_3)_2$(1)	6	**2a-i**	76
2	MeC≡CH	*n*HexZnBr	$PdCl_2(PPh_3)_2$(1)	6	**2a-ii**	77
3	MeC≡CH	PhZnBr	$PdCl_2(PPh_3)_2$(1)	2	**2a-iii**	73
4	MeC≡CH		$PdCl_2(PPh_3)_2$(1)	6	**2a-iv**	75
5	PhC≡CH	MeZnBr	$Pd(tBu_3P)_2$(0.5)	2	**2b-i**	≤68[a]
6	PhC≡CH		$Pd(tBu_3P)_2$(0.5)	2	**2b-ii**	≤57[a]

[a] The yields indicated are for the final product **3-xii** and **3-xiii**. See Table 2.



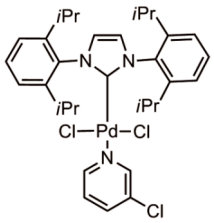


Figure 1. The structure of PEPPSI™-IPr (**8**).

Pd-Catalyzed Cross-Coupling Reactions of *β,β*-disubstituted-1-alkenyl(pinacol)boranes (2) Promoted by nBu_4NF(TBAF) or CsF

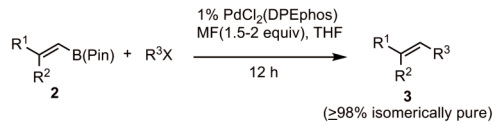
For overcoming the reported difficulties and inconveniences observed in the oxy base-promoted Pd-catalyzed cross-coupling of alkenylboranes,[2a] the use of fluoride salts[9,10] was investigated. Although the number of studies on fluoride-promoted Pd-catalyzed cross-coupling with alkenylboranes was limited,[10] an investigation by Srebnik[10a] on CsF-promoted Pd-catalyzed cross-coupling of *β,β*- and *α,β*-disubstituted alkenylboranes proved to be of crucial importance. Also to be noted here is the possible usefulness of *N*- or *O*-centered base-promoted Pd-catalyzed cross-coupling of potassium alkenyltrifluoroborates reported by Molander.[10b,d–f] Our own brief screening of various fluorides and some oxy bases for the reaction of *β,β*-disubstituted alkenylborane (**2a–ii**) with *p*-nitroiodobenzene in the presence of 1 mol% of $PdCl_2$(DPEphos) indicated that (a) TBAF (95%), Et_4NF (87%), and CsF (90%) were among the most effective, the numbers in parentheses indicating isolated yields. On the other hand, nBu_4NI (0%), LiF (0%), and K_2CO_3 (5%) were almost totally ineffective, while some others, including NaF (83%), and Cs_2CO_3 (70%), also were of considerable efficiency. Based on these findings, TBAF was chosen because of its superior efficiency. In view of its considerably high cost, however, CsF was also chosen as the best compromise. As summarized in Table 2, both TBAF and CsF have proved to be highly effective promoters. Both the product yields and isomeric purities were generally excellent. The only notable difficulty recorded in Table 2 was observed in the reaction of 2a–ii with 1-iodophenylacetylene, where the low product yield was attributable to the competitive homodimerization of 1-iodophenylacetylene. Fortunately, this problem was fully suppressed by using 1-bromophenylacetylene in place of 1-iodophenylacetylene. All trisubstituted alkenes (**3**) shown in Table 2 were formed and isolated as ≥98% isomerically pure compounds, and their stereochemical assignments were made on the basis of their NOE measurements.

The results shown in Table 2 clearly indicate that the propyne bromoboration–Pd-catalyzed Negishi–Suzuki tandem alkenylation route to methyl-branched (*Z*)-trisubstituted alkenes of high (≥98%) isomeric purity and wide applicability has finally been developed as a high-yielding and efficient method for their head-to-tail (**H**-to-**T**) construction (Scheme 5), nicely complementing the widely used Zr-catalyzed alkyne carboalumination–Pd-catalyzed Negishi alkenylation tandem route to methyl-branched (*E*)-trisubstituted alkenes.[3]

It should also be recalled that another widely applicable tail-to-head (**T**-to-**H**) construction (Scheme 5) route to either *E* or *Z* trisubstituted alkenes via Pd-catalyzed double substitution of 1,1-dibromo-1-alkenes developed several years ago by us[12] is also highly selective and complementary with the method developed herein.

Noting that the *N*- or *O*-centered base-promoted Pd-catalyzed alkenylation with preformed potassium *β,β*-disubstituted alkenyltrifluoroborates does not appear to have been reported, **2a–ii** was treated with 2–4 equivalents of KHF_2 as described in the literature[10b] to generate in situ the corresponding potassium (*Z*)-2-methyl-1-octenyltrifluoroborate (**9**), which was in situ subjected to Pd-catalyzed cross-coupling with PhI. However, the desired **3-ii** was obtained only in low yields (≤30–40%). As indicated in Tables 1 and 2, **2a–ii** was obtained in 85% yield from propyne and converted into **3-ii** in 83% yield (71% yield from propyne). The corresponding reaction of (*E*)-1-octenyltrifluoroborate (**8**) produced the desired

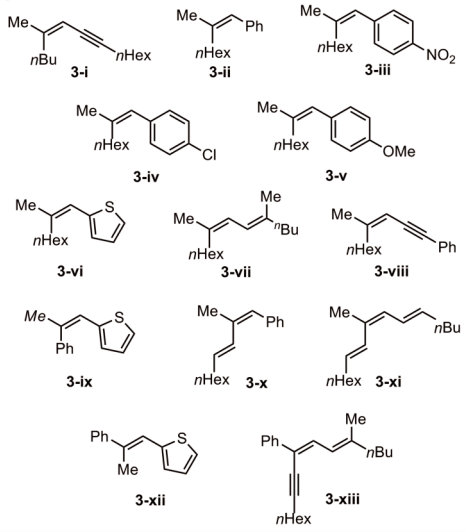
Table 2. Coversion of β,β-disubstituted-1-alkenyl(pinacol)boranes (**2**) into trisubstitued alkenes (**3**) via fluoride-promoted Pd-catalyzed alkenylation with **2**.

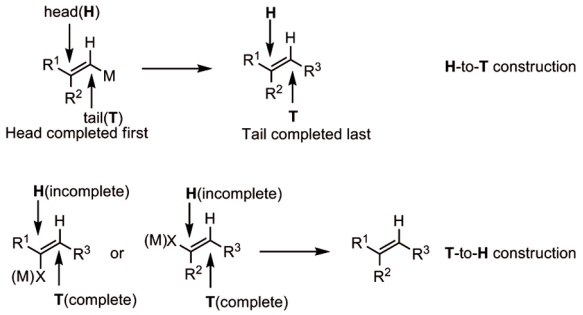


R^1, R^2 B(Pin)	R^3X	MF	temp (°C)	product[b]	yield (%)
Me, *n*Bu B(Pin) **2a-i**	Br—≡—*n*Hex	TBAF	60	**3-i**	93
Me, *n*Hex B(Pin) **2a-ii**	PhI	CsF	reflux	**3-ii**	83
2a-ii	$pNO_2C_6H_4I$	TBAF	60	**3-iii**	98
2a-ii	$pNO_2C_6H_4I$	CsF	reflux	**3-iii**	85
2a-ii	$pClC_6H_4I$	TBAF	60	**3-iv**	84
2a-ii	$pMeOC_6H_4I$	TBAF	60	**3-v**	85
2a-ii	S, I	TBAF	60	**3-vi**	83
2a-ii	I, Me, *n*Bu	TBAF	60	**3-vii**	96
2a-ii	I, Me, *n*Bu	CsF	reflux	**3-vii**	83
2a-ii	Br—≡—Ph	TBAF	60	**3-viii**	93
2a-ii	I—≡—Ph	TBAF	60	**3-viii**	43[a]
Me, Ph B(Pin) **2a-iii**	S, I	TBAF	60	**3-ix**	88
Me, *n*Hex B(Pin) **2a-iv**	PhI	TBAF	60	**3-x**	82
	I, *n*Bu	TBAF	60	**3-xi**	74
Ph, Me B(Pin) **2b-i**	S, I	TBAF	60	**3-xii**	90
		CsF	reflux	**3-xii**	79
Ph, *n*Hex B(Pin) **2b-ii**	I, Me, *n*Bu	TBAF	60	**3-xiii**	76
		CsF	reflux	**3-xiii**	65

[a] Ph—≡—≡—Ph (35% of I—≡—Ph) and (*Z*)-Me(*n*Hex)C=CHI)(10%) were detected.

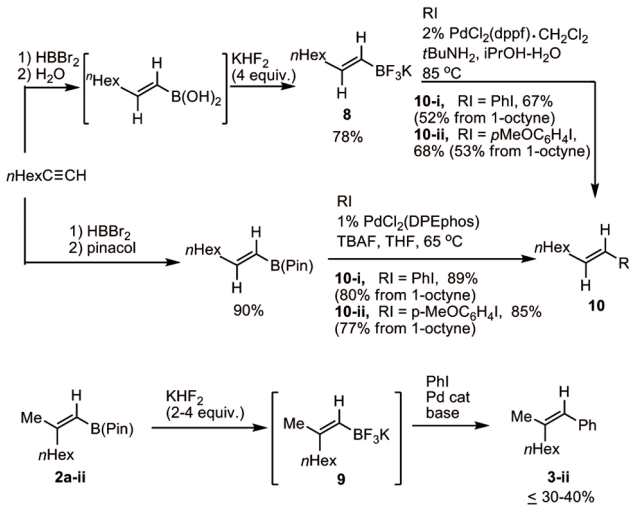
[b]





Scheme 5.

product **10-i** in 67% yield (Scheme 6), which is roughly comparable with the results reported for a similar case.[10b] Although further investigation is clearly desirable, it is our tentative view that the two seemingly very similar protocols may be significantly different. In particular, it would appear desirable to clarify the role of F vis-à-vis an added base, i.e., tBuNH$_2$, in Molander's protocol.



Scheme 6.

3. Conclusions

(1) In search for previously elusive widely applicable and highly (≥98%) selective head-to-tail construction routes to trisubstituted alkenes, especially those that are readily applicable to the synthesis of (*Z*)-β-methyl trisubstituted alkenes, fluoride-promoted Pd-catalyzed alkenylation with (*Z*)-β-methyl-1-alkenyl(pinacol)boranes(**2a**) was examined and found to be excellent, producing the desired trisubstituted alkenes (**3i–3xi**) in 74–98% yields in ≥98% stereoselectivity. The requisite (*Z*)-β,β-disubstituted-1-alkenyl(pinacol)boranes (**2a**) can now be prepared from propyne via propyne bomoboration–Pd-catalyzed Negishi alkenylation either in one pot or in two steps in good overall yields (73–77% observed). This protocol is nicely

complementary with the (*E*)-selective Zr-catalyzed alkyne carboalumination–Pd-catalyzed alkenylation. It is also complementary with the tail-to-head protocol via Pd-catalyzed stepwise and highly selective tandem alkenylation of 1,1-dibromo-1-alkenes.

(2) Although not encountered in this study, it should be clearly kept in mind that the alkyne haloboration–Pd-catalyzed alkenylation protocols have, in the past, posed and will continue to pose at least two potential limitations to cope with and overcome. One is debromoboration of *β*-bromoalkenylboron derivatives, and the other is an assortment of complications due to intermediary formation of fundamentally capricious allyl-, propargyl-, and even benzylpalladium derivatives. Although we speculate that two examples of conversion of phenylacetylene to **2b-i** and **2b-ii**, which required highly active catalysts, such as $Pd(tBu_3P)_2$ and PEPPSI™-IPr (**8**), may have displayed a difficulty pertaining to both of the two mentioned above, it was luckily overcome in these cases.

(3) The relationship between the fluoride-promoted Pd-catalyzed alkenylation with alkenyl(pinacol)boranes reported herein and the recently developed *N*- or *O*-centered base-promoted Pd-catalyzed alkenylation with preformed potassium alkenyltrifluoroborates remains unclear. Comparison of their synthetic merits, and efforts to gain mechanistic insights, appear to be very desirable.

(4) Finally, our own efforts to further improve Pd-catalyzed cross-coupling of various types continue. Even though Pd-catalyzed cross-coupling with organometals containing Zn appears to be generally the fastest and most highly selective (with that involving Zr, Al, and perhaps In as well, closely trailing the organozinc cross-coupling), it is gratifying to learn that the significantly slower Pd-catalyzed organoboron cross-coupling, generally requiring heating to 50–100 °C, can be and has been continuously improved, as indicated by recent results, including those reported herein. Many further improvements of Pd-catalyzed cross-coupling involving all of the metals mentioned above, as well as those not mentioned here, may be predicted, and such efforts are very much encouraged.

Experimental Section

General

All reactions were run under a dry Ar atmosphere. Reactions were monitored by thin layer chromatography (TLC) carried out on 0.25-mm Merck silica gel plates (60F-254) or by GC analysis of reaction aliquots. GC analysis was performed on an HP 6890 Gas Chromatograph using an HP-5 capillary column (30 m × 0.32 mm, 0.5 μM film) packed with SE-30 on Chromosorb W. Column chromatography was carried out on 230–400 mesh silica gel. ^{1}H and ^{13}C NMR spectra were recorded on Varian-Inova-300. Commercially available solvents and reagents were of reagent grade and used without further purification, unless otherwise indicated. THF was dried by distillation under Ar from sodium/benzophenone. CH_2Cl_2 was dried by distillation under Ar from CaH_2. $ZnBr_2$ was flame-dried in vacuo.

Representative Procedure for Fluoride-Promoted Pd-Catalyzed Alkenylation of β,β-disubstituted-1-alkenyl(pinacol)boranes

A flame-dried, 25-mL, round-bottomed flask, equipped with a magnetic stirring bar, a rubber septum, and an argon inlet, was charged with $PdCl_2$(DPEphos) (0.01 mmol), **2** (1.2 mmol), an organic iodide or bromide (1.0 mmol), and THF (4 mL) under an atmosphere of argon. TBAF or CsF (1.5–2.0 mmol) was as added. The mixture was heated to 60 °C and monitored by TLC. The reaction mixture was then quenched with aqueous NH_4Cl. The aqueous layer was separated and extracted with ethyl acetate. The combined organic phase was washed with brine, dried over anhydrous magnesium sulfate, filtered, and concentrated by rotary evaporator (40 °C, 20 mmHg) to give the crude product. The product was purified by flash chromatography.

3-i. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 6H), 1.3–1.5 (m, 12H), 1.72 (s, 3H), 2.28 (q, *J* = 7.2 Hz, 4H), 5.27 (s, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 13.8, 13.9, 19.4, 22.1, 22.4, 22.5, 28.5, 28.9, 29.7, 31.3, 34.0, 78.2, 91.9, 105.5, 150.5. HRMS(ESI) calcd for $C_{15}H_{26}$: 206.2035; found: 206.2038 $[M]^+$.

3-ii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 3H), 1.2–1.3 (m, 6H), 1.4–1.5 (m, 2H), 1.91 (s, 3H), 2.25 (t, *J* = 7.5 Hz, 2H), 6.30 (s, 1H), 7.2–7.3 (m, 5H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.1, 22.6, 24.1, 28.1, 29.3, 31.7, 32.5, 125.2, 125.7, 128.0, 128.5, 138.6, 139.8. HRMS(ESI) calcd for $C_{15}H_{22}$: 202.1722; found: 202.1719 $[M]^+$.

3-iii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.87 (t, *J* = 6.8 Hz, 3H), 1.1–1.3 (m, 6H), 1.4–1.5 (m, 2H), 1.92 (s, 3H), 2.1–2.2 (m, 2H), 6.29 (s, 1H), 7.31 (d, *J* = 8.4 Hz, 2H), 8.76 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.0, 22.5, 24.4, 27.9, 29.2, 31.5, 32.7, 123.4, 123.7, 129.0, 144.3, 145.4, 145.6. HRMS(ESI) calcd for $C_{15}H_{21}NO_2$: 247.1572; found: 247.1581 $[M]^+$.

3-iv. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.7–0.9 (m, 3H), 1.2–1.5 (m, 8H), 1.89 (s, 3H), 2.1–2.2 (m, 2H), 6.23 (s, 1H), 7.12 (d, *J* = 8.1 Hz, 2H), 7.29 (d, *J* = 8.1 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.0, 22.6, 24.0, 27.9, 29.3, 31.6, 32.4, 124.1, 128.1, 129.8, 131.4, 137.0, 140.6. HRMS(ESI) calcd for $C_{15}H_{21}Cl$: 236.1332; found: 236.1338 $[M]^+$.

3-v. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.96 (t, *J* = 7.2 Hz, 3H), 1.2–1.4 (m, 6H), 1.4–1.6 (m, 2H), 1.92 (s, 3H), 2.2–2.3 (m, 2H), 3.84 (s, 3H), 6.28 (s, 1H), 6.91 (d, *J* = 8.8 Hz, 2H), 7.13 (d, *J* = 8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.0, 22.6, 24.1, 28.0, 29.3, 31.7, 32.4, 55.0, 113.3, 124.6, 129.5, 131.1, 138.3, 157.6. HRMS-(ESI) calcd for $C_{16}H_{24}O$: 232.1827; found: 232.1835 $[M]^+$.

3-vi. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 3H), 1.3–1.6 (m, 8H), 1.92 (s, 3H), 2.3–2.4 (m, 2H), 6.40 (s, 1H), 6.90 (d, *J* = 3.3 Hz, 1H), 7.00 (dd, *J* = 5.1, 3.6 Hz, 1H), 7.19 (d, *J* = 5.1 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.0, 22.6, 24.7, 27.6, 29.5, 31.7, 33.6, 118.2, 123.5, 125.7, 126.5, 139.3, 141.1. HRMS(ESI) calcd for $C_{13}H_{20}S$: 208.1286; found: 208.1288 $[M]^+$.

3-vii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 6H), 1.3–1.5 (m, 12H), 1.74 (s, 3H), 1.80 (s, 3H), 2.08 (t, *J* = 7.6 Hz, 2H), 2.16 (t, *J* = 7.6 Hz, 2H) 6.01 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 13.9, 14.0, 16.2, 22.3, 22.6, 24,1, 28.1, 29.2, 30.2, 31.8, 32.0, 40.0, 120.5, 121.4, 136.0, 136,7. HRMS(ESI) calcd for $C_{16}H_{30}$: 222.2348; found: 222.2352 $[M]^+$.

3-viii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 3H), 1.3–1.5 (m, 8H), 1.86 (s, 3H), 2.43 (t, *J* = 5.7 Hz, 2H), 5.51 (s, 1H), 7.3–7.4 (m, 3H), 7.45 (d, *J* = 6.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.0, 22.6, 27.5, 28.9,31.6, 34.7, 87.6, 91.3, 105.7, 124.1, 127.5,

128.1, 131.1, 153.1. HRMS(ESI) calcd for $C_{17}H_{22}$: 226.1722; found: 226.1723 $[M]^+$.

3-ix. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 2.18 (d, J = 1.5 Hz, 3H), 6.63 (s, 1H), 6.73 (d, J = 3.0 Hz, 1H), 6.81 (dd, J = 5.1, 3.9 Hz, 1H), 6.95 (d, J = 5.1 Hz, 1H), 7.2–7.2 (m, 2H), 7.3–7.4 (m, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 27.2, 120.3, 124.5, 125.8, 126.6, 127.4, 128.0, 128.8, 137.6, 140.8, 141.8. HRMS(ESI) calcd for $C_{13}H_{12}S$: 200.0660; found: 200.0665 $[M]^+$.

3-x. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.90 (t, J = 6.9 Hz, 3H), 1.3–1.4 (m, 8H), 2.00 (d, J = 1.5 Hz, 3H), 2.12 (dd, J = 6.9, 6.3 Hz, 2H), 5.86 (dt, J = 15.6, 6.9 Hz, 1H), 6.35 (s, 1H), 6.50 (d, J = 15.9 Hz, 1H), 7.2–7.4 (m, 5H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.3, 21.5, 22.8, 29.1, 29.6, 31.9, 33.4, 126.3, 127.5, 128.2, 128.4, 129.5, 133.4, 135.0, 138.1. HRMS(ESI) calcd for $C_{17}H_{24}$: 228.1878; found: 228.1875 $[M]^+$.

3-xi. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 6H), 1.3–1.4 (m, 12H), 1.84 (s, 3H), 2.1–2.2 (m, 4H), 5.6–5.7 (m, 1H), 5.69 (d, J = 15.3 Hz, 1H), 5.84 (d, J = 11.7 Hz, 1H), 6.50 (dd, J = 14.7, 11.7 Hz, 1H), 6.60 (d, J = 15.3 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.1, 14.3, 20.8, 22.4, 22.8, 29.1, 29.8, 31.9, 32.0, 32.9, 33.6, 125.8, 127.1, 127.9, 131.5, 131.9, 134.2. HRMS(ESI) calcd for $C_{17}H_{30}$: 234.2348; found: 234.2347 $[M]^+$.

3-xii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 2.29 (s, 3H), 7.04 (s, 1H), 7.1–7.6 (m, 8H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 18.3, 120.9, 125.0, 125.9, 126.9, 127.0, 127.5, 128.3, 135.6, 141.4, 144.0. HRMS-(ESI) calcd for $C_{13}H_{12}S$: 200.0660; found: 200.0661 $[M]^+$.

3-xiii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.8–0.9 (m, 6H), 1.2–1.3 (m, 6H), 1.4–1.6 (m, 4H), 1.6–1.7 (m, 2H), 1.90 (s, 3H), 2.20 (t, J = 6.9 Hz, 2H), 2.53 (t, J = 6.9 Hz, 2H), 6.58 (d, J = 9.0 Hz, 1H), 7.11 (d, J = 11.7 Hz, 1H), 7.1–7.3 (m, 1H), 7.6–7.7 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 13.9, 14.0, 17.2, 19.7, 22.4, 22.6, 28.6, 28.8, 30.1, 31.3, 40.1, 78.1, 98.3, 121.0, 123.7, 125.9, 127.1, 128.2, 130.2, 139.1, 143.8. HRMS(ESI) calcd for $C_{23}H_{32}$: 308.2504; found: 308.2508 $[M]^+$.

8. ^{1}H NMR (d_6-DMSO, 300 MHz) δ = 0.8–0.9 (m, 3H), 1.2–1.3 (m, 8H), 1.8–1.9 (m, 2H), 5.1–5.3 (m, 1H), 5.4–5.5 (m, 1H); ^{13}C NMR (d_6-DMSO, 75 MHz) δ = 14.0, 22.1, 28.5, 29.2, 31.3, 35.4, 133.6, 133.7. HRMS(ESI) calcd for $C_8H_{15}BF_3K$: 218.0856; found: 179.1224 $[M\text{-}K]^-$.

10-i. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.9–1.0 (m, 3H), 1.3–1.6 (m, 8H), 2.2–2.4 (m, 2H), 6.2–6.4 (m, 1H), 6.4–6.5 (m, 1H), 7.2–7.4 (m, 5H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.2, 22.8, 29.1, 29.5, 31.9, 33.2, 126.0, 126.8, 128.5, 129.8, 131.2, 138.0. HRMS-(ESI) calcd for $C_{14}H_{20}$: 188.1565; found: 188.1573 $[M]^+$.

10-ii. ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 0.9–1.0 (m, 3H), 1.3–1.6 (m, 8H), 2.1–2.3 (m, 2H), 3.82 (s, 3H), 6.0–6.4 (m, 4H), 7.3–7.4 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 14.1, 22.6, 29.0, 29.5, 31.8, 33.0, 55.1, 113.8, 126.9, 129.0, 130.8, 158.5. HRMS(ESI) calcd for $C_{15}H_{22}O$: 218.1671; found: 218.1676 $[M]^+$.

Acknowledgments

This work was mainly supported by National Institutes of Health (GM36792) and Purdue University. We also acknowledge support of various forms by Aldrich Chemical Co. and Johnson Matthey Catalysts Co.

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Received: August 26, 2010
Accepted: October 6, 2010
Published online: November 29, 2010