

Nucleophilic Borylation of Benzyl Halides with Bis(pinacolato)diboron Catalyzed by Palladium(0) Complexes

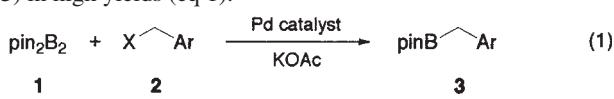
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Nucleophilic borylation of benzyl halides with bis(pinacolato)diboron in the presence of KOAc in toluene was effectively catalyzed by a palladium complex generated in situ from Pd(dba)₂ and (4-MeOC₆H₄)₃P, giving the corresponding pinacol benzylboronates in high yields.

Benzylboron compounds are useful synthetic intermediates,¹ potential chiral Lewis acids,² and potential ¹⁰B carriers for boron neutron capture therapy,³ which have been prepared by catalytic hydroboration of styrenes,⁴ transmetalation of benzylmetals to BX₃,⁵ homologation of arylboranes,⁶ or cross-coupling of haloarenes with borylmethylzinc reagents.⁷ Nucleophilic borylation of benzyl electrophiles would also provide an efficient and convenient route to benzylboron compounds; however, the lack of suitable boron nucleophiles has limited this protocol. Recently, we found that (alkoxo)diborons can undergo transmetalation with organo(oxo)palladium(II) complexes, thus allowing the cross-coupling reactions of (alkoxo)diborons with aryl,⁸ vinyl,⁹ and allyl¹⁰ electrophiles in the presence of a palladium catalyst and a base.¹¹ We report herein the palladium-catalyzed nucleophilic borylation of benzyl halides (**2**) with bis(pinacolato)diboron¹² (pin₂B₂, pin = Me₄C₂O₂) (**1**) to provide pinacol benzylboronates (**3**) in high yields (eq 1).¹³



The borylation of benzyl chloride (1.0 mmol) with pin₂B₂ **1** (1.1 mmol) was carried out at 50 °C for 24 h by using Pd(dba)₂ (0.03 mmol) as a catalyst precursor to examine the effects of ligands (0.06 mmol), bases (1.5 mmol), and solvents (6 ml) (Table 1). Although Pd(dba)₂ itself did not catalyze the reaction in the presence of KOAc in toluene (Entry 1), addition of a (4-MeOC₆H₄)₃P ligand successfully promoted the borylation to afford the expected pinacol benzylboronate in 85% yield (Entry 2). The catalyst efficiency highly depends on the electron-donating ability of phosphine ligands. Use of electron-neutral or -poor triarylphosphines such as Ph₃P and (4-ClC₆H₄)₃P resulted in significantly lower yields (Entries 3 and 4). Although dppf and Ph₃As have been used successfully for the analogous borylation of aryl^{8a,b} or allyl¹⁰ electrophiles, these ligands were not effective for that of benzyl halides (Entries 5 and 6). The superiority of the electron-rich phosphine, (4-MeOC₆H₄)₃P, prompted us to examine trialkylphosphines; however, (c-C₆H₁₁)₃P complexes^{8c} failed to catalyze the reaction probably due to their decomposition yielding phosphonium salts of benzyl chloride (Entry 7). KOAc was recognized to be the best base. Changing the base to an inorganic or weaker base such as K₃PO₄ and KO₂CCF₃ remarkably slowed down the reaction (Entries 8 and 9). As for solvents, non-polar ones such as toluene gave the best results. Use

of polar solvents such as DMSO resulted in the formation of benzyl acetate (ca. 40%) by the direct reaction of benzyl chloride with KOAc (Entry 10).

Table 1. Reaction conditions for nucleophilic borylation of benzyl chloride with pin₂B₂ **1** by using a Pd(dba)₂ precatalyst^a

Entry	Ligand	Base	Solvent	Yield/% ^b
1	none	KOAc	toluene	0
2	(4-MeOC ₆ H ₄) ₃ P	KOAc	toluene	85
3	Ph ₃ P	KOAc	toluene	41
4	(4-ClC ₆ H ₄) ₃ P	KOAc	toluene	2
5	dppf ^c	KOAc	toluene	59
6	Ph ₃ As	KOAc	toluene	23
7	(c-C ₆ H ₁₁) ₃ P	KOAc	toluene	0
8	(4-MeOC ₆ H ₄) ₃ P	K ₃ PO ₄	toluene	21
9	(4-MeOC ₆ H ₄) ₃ P	KO ₂ CCF ₃	toluene	6
10	(4-MeOC ₆ H ₄) ₃ P	KOAc	DMSO	50

^aA mixture of pin₂B₂ **1** (1.1 mmol), benzyl chloride (1.0 mmol), Pd(dba)₂ (0.03 mmol), a ligand (0.06 mmol), a base (1.5 mmol), and a solvent (6 ml) was stirred at 50 °C for 24 h. ^bGLC yields based on benzyl chloride. ^c1,1'-Bis(diphenylphosphino)ferrocene (0.03 mmol) was used.

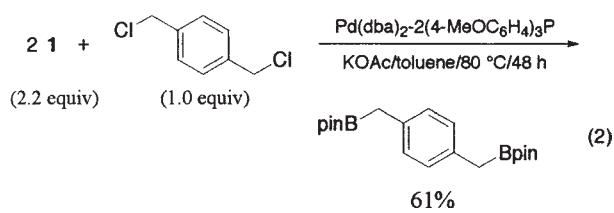
The synthesis of pinacol benzylboronates **3** by the reaction between pin₂B₂ **1** and representative benzyl halides **2** in the presence of a Pd(dba)₂-2(4-MeOC₆H₄)₃P catalyst and a KOAc base in toluene is summarized in Table 2.¹⁴ The protocol is applicable not only to chlorides but also to bromides, providing variously functionalized **3** in high yields. The reaction smoothly proceeded at 50 °C for **2** having an electron-withdrawing substituent at the para position (Entries 1-4), whereas those having a donating group required heating to 80 °C (Entries 6 and 7). Either an electron-withdrawing or -donating substituent at the ortho position decelerated the reaction because of steric hindrance (Entries 8 and 9), while 1-(chloromethyl)naphthalene was smoothly borylated at 50 °C (Entry 10). The reaction is feasible with various functional groups such as CN and CO₂Me which should be protected in the synthesis from benzyl lithium or -magnesium reagents (Entries 1 and 3).⁵ All attempts at the borylation of 1-chloro-1-phenylpropane were unsuccessful probably due to its slow oxidative addition to the palladium(0) complex.

A one-pot synthesis of bis(borylmethyl)benzene via the sequential double borylation is shown in eq 2. The reaction of pin₂B₂ **1** (2.2 equiv) with 1,4-bis(chloromethyl)benzene (1.0 equiv) at 80 °C in the presence of the palladium catalyst (6 mol%) and KOAc (3.0 equiv) in toluene (6 ml) gave the corresponding diborylated product in 61% yield.

Table 2. Synthesis of pinacol benzylboronates (eq 1)^a

Entry	Benzyl Halide 2	Temp/°C	Yield/% ^b
1		50	72
2		50	83
3		50	80
4		50	85
5		50	85
6		80	73
7		80	78
8		80	78
9		80	83
10		50	88

^aA mixture of pin₂B₂ **1** (1.1 mmol), a benzyl halide **2** (1.0 mmol), Pd(dba)₂ (0.03 mmol), (4-MeOC₆H₄)₃P (0.06 mmol), KOAc (1.5 mmol), and toluene (6 ml) was stirred for 24 h at the temperature shown in the Table. ^bGLC yields based on benzyl halides **2**.



In summary, the nucleophilic borylation of benzyl halides with bis(pinacolato)diboron is effectively catalyzed by a Pd(dba)₂-2(4-MeOC₆H₄)₃P catalyst in the presence of KOAc in toluene. The reaction provides an efficient and convenient method

for the synthesis of a wide variety of benzylboronates.

References and Notes

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- A representative procedure for **3** (pinBCH₂Ph): A flask containing Pd(dba)₂ (0.03 mmol), (4-MeOC₆H₄)₃P (0.06 mmol), pin₂B₂ **1** (1.1 mmol), and KOAc (1.5 mmol) was flushed with nitrogen, and then charged with toluene (6 ml) and benzyl chloride (1.0 mmol). The mixture was stirred at 50 °C for 24 h. The product was isolated by Kugelrohr distillation to give an analytically pure sample: ¹H NMR (400 MHz, CDCl₃, TMS) δ 1.23 (s, 12 H), 2.29 (s, 2 H), 7.1–7.3 (m, 5 H); ¹³C NMR (100 MHz, CDCl₃, TMS) δ 24.69, 83.38, 124.79, 128.22, 128.96, 138.61 (Due to quadrupolar relaxation, the carbon attached to the boron atom was not detected); HRMS *m/z* Found: M⁺, 218.1470. Calcd for C₁₃H₁₉BO₂: 218.1478.