



Borylation Hot Paper



Boraformylation and Silaformylation of Allenes

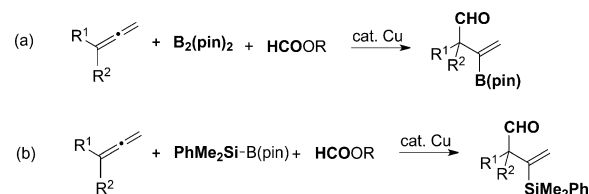
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Abstract: The boraformylation of allenes with $B_2(\text{pin})_2$ and a formate ester as boron and formyl source, respectively, proceeds in the presence of a copper catalyst. The reaction selectively affords the corresponding β -boryl β,γ -unsaturated aldehydes in good to high yields. Furthermore, the silaformylation of allenes was achieved with a formate ester and $\text{PhMe}_2\text{Si}-\text{B}(\text{pin})$ as the silicon source.

Organoboron acids and esters are versatile boron functional groups in organic synthesis, especially for cross-coupling reactions.^[1] Thus various methods for the preparation of organoboron compounds have been explored, such as the hydroboration of carbon–carbon unsaturated bonds^[2] and reactions of boron electrophiles with organolithium or Grignard reagents.^[1a] Being more common in organic synthesis, silicon functional groups have been employed in a variety of highly efficient transformations.^[3]

The simultaneous incorporation of two different functional groups onto C–C unsaturated bonds is one of the most capable approaches for the preparation of complex molecules. In particular, allenes are valuable reaction partners as they can be converted into a structurally diverse array of products.^[4] However, such dual allene functionalizations usually provide a range of regio- and stereoisomers. Thus the selective formation of desired products is a highly important task.

Herein, we report on the boraformylation of allenes by simultaneous incorporation of boryl and formyl functional groups onto a C–C double bond of an allene to afford β -boryl β,γ -unsaturated aldehydes with high regioselectivity (Scheme 1 a). The formyl moiety is a potent functional group that can be further converted to yield useful compounds. It is frequently formed by oxidation of primary alcohols,^[5] reduction of carboxylic acids,^[5] and, in industry, by the hydro-



Scheme 1. a) Boraformylation and b) silaformylation of allenes.

formylation of alkenes under CO/H_2 pressure.^[6] We found that the boraformylation of allenes could be achieved with $B_2(\text{pin})_2$ and a formate ester as boron and formyl source, respectively, in the presence of a copper catalyst. Formate esters have been used as formyl sources in Claisen-type condensation reactions.^[7] To the best of our knowledge, this is the first report on the boraformylation of unsaturated substrates. Furthermore, the silaformylation of allenes was achieved for the first time by employing $\text{PhMe}_2\text{Si}-\text{B}(\text{pin})$ as the silicon source along with a formate ester (Scheme 1 b).

First, the reaction of 3-methyl-1,2-nonadiene (**1a**), $B_2(\text{pin})_2$, and hexyl formate was conducted at 50°C in the presence of CuOAc (3.0 mol %) and a ligand (4.0 mol %) in toluene (Table 1).^[8] Impressively, the steric properties of the ligand strongly affected the reaction. PPh_3 , dppe , xantphos , and dppbz ^[9] were ineffective in promoting the catalytic reaction, yielding the desired β -boryl β,γ -unsaturated aldehyde (**2a**) in trace amounts (entries 1–4). However, Xy-dppbz produced **2a** in 9% yield (entry 5). Finally, DTB-dppbz ^[10] and DTBM-dppbz selectively afforded **2a** in yields of 99% and 96%, respectively (entries 6 and 7). As for N-heterocyclic carbene (NHC) ligands, IPr gave **2a** in 32% yield (entry 8) whereas IMes did not enable the formation of this compound (entry 9). Benzyl formate (instead of hexyl formate) successfully afforded **2a** in 80% yield (entry 10) whereas the utilization of phenyl formate considerably decreased the yield (entry 11).

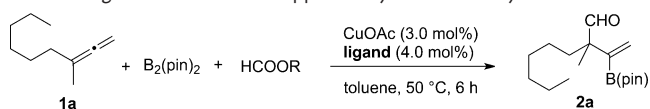
With DTBM-dppbz as the ligand, various allenes were employed as substrates under the optimized reaction conditions (Table 2). 1,1-Dialkyl-substituted allenes (**1a–1d**) provided the corresponding β -boryl β,γ -unsaturated aldehydes (**2a–2d**) in good to high yields after isolation (entries 1–4). In some cases, the addition of sodium laurate^[11] (20 mol %) increased the catalytic activity. For example, **2e** was isolated in 78% yield when the reaction of **1e** was conducted in the presence of sodium laurate (entry 5) whereas a GC yield of 65% was determined in the absence of sodium laurate. With sodium laurate, allenes bearing several groups, such as terminal olefin (**1e**), chlorophenyl (**1f**), iodophenyl (**1g**), silyloxy (**1h**), acetal (**1i**), ester (**1j**), or carbamate (**1k**) moieties, provided the corresponding prod-

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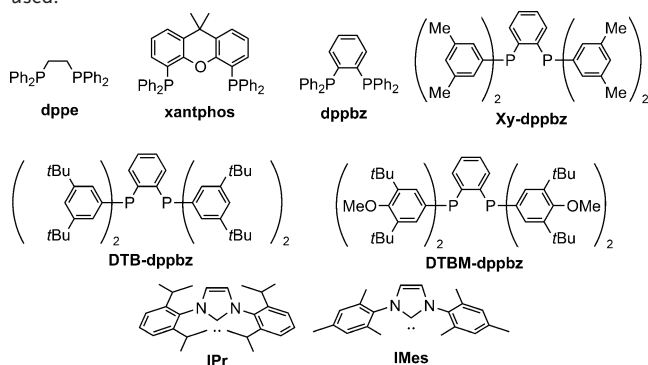
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Table 1: Ligand Effect on the copper-catalyzed boraformylation of **1a**.^[a]

Entry	Ligand	Formate R =	Yield [%] ^[b]
1	PPh ₃	C ₆ H ₁₃	trace
2	dppe	C ₆ H ₁₃	2
3	xantphos	C ₆ H ₁₃	trace
4	dppbz	C ₆ H ₁₃	trace
5	Xy-dppbz	C ₆ H ₁₃	9
6	DTB-dppbz	C ₆ H ₁₃	99
7	DTBM-dppbz	C ₆ H ₁₃	96
8 ^[c]	IPrCuCl/ <i>t</i> BuOK	C ₆ H ₁₃	32
9 ^[d]	IMesCuCl/ <i>t</i> BuOK	C ₆ H ₁₃	0
10	DTBM-dppbz	PhCH ₂	80
11	DTBM-dppbz	Ph	31

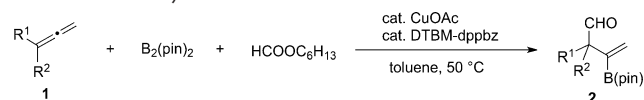
[a] Reaction conditions: **1a** (0.30 mmol), B₂(pin)₂ (0.36 mmol, 1.2 equiv), formate (0.33 mmol, 1.1 equiv), CuOAc (3.0 mol%), ligand (4.0 mol%), toluene (0.45 mL), 50 °C, 6 h. [b] Determined by GC analysis. [c] A mixture of IPrCuCl (3.0 mol%) and *t*BuOK (10 mol%) was used. [d] A mixture of IMesCuCl (3.0 mol%) and *t*BuOK (10 mol%) was used.



ucts (**2e–2k**) in moderate to good yields (entries 5–11). A monosubstituted allene, 4,4-dimethyl-1,2-hexadiene (**11**), did not afford the corresponding boraformylation product, even after full consumption of the starting material.

The present procedure was amenable to a gram-scale reaction. Thus, starting from 0.83 g (6.0 mmol) of **1a**, 1.3 g of **2a** were obtained, which corresponds to a yield of 72% (Scheme 2a). Suzuki–Miyaura coupling^[1a] of **2a** with 4-*tert*-butyliodobenzene smoothly afforded the desired product in 83% yield after isolation (Scheme 2b). Coupling with β-bromostyrene also provided the corresponding diene in 58% yield (Scheme 2c). Horner–Wadsworth–Emmons reaction^[12] of **2a** enabled the isolation of the olefinated product in high yield (Scheme 2d).

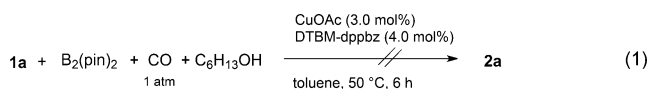
Formate esters, especially aryl formates, are known to decompose to liberate CO,^[13] thereby enabling a boraformylation reaction with the CO that is evolved in situ. However, hexyl formate was not converted when the reaction shown in Table 2, entry 1 was conducted without both B₂(pin)₂ and **1a**. Furthermore, the boraformylation product (**2a**) was not obtained upon replacement of hexyl formate with a mixture of CO (1 atm) and hexanol [Eq. (1)]. Thus CO is not involved in the present allene boraformylation.

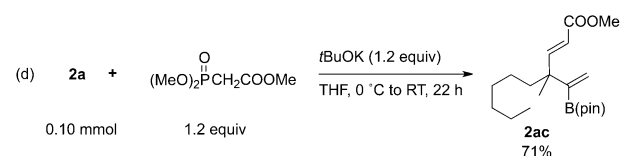
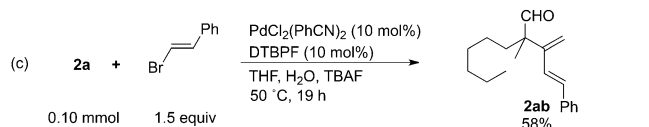
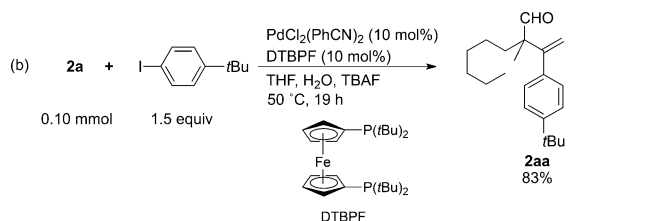
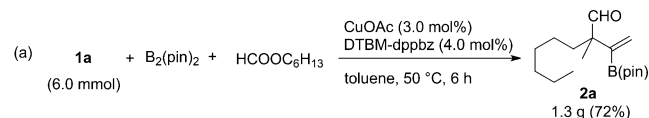
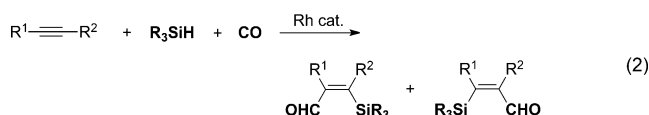
Table 2: Boraformylation of various allenes.^[a]

Entry	Allene 1	Product 2	Yield [%] ^[b]
1	1a	2a	87
2	1b	2b	84
3 ^[c]	1c	2c	64
4	1d	2d	46
5 ^[d]	1e	2e	78
6 ^[d]	1f	2f	74
7 ^[d]	1g	2g	52
8 ^[d]	1h	2h	73
9 ^[d]	1i	2i	90
10 ^[d]	1j	2j	56
11 ^[d]	1k	2k	45

[a] Reaction conditions: **1** (0.30 mmol), B₂(pin)₂ (0.36 mmol, 1.2 equiv), hexyl formate (0.33 mmol, 1.1 equiv), CuOAc (3.0 mol%), DTBM-dppbz (4.0 mol%), toluene (0.45 mL), 50 °C, 6 h. [b] Yields of isolated products are given. [c] 16 h. [d] Sodium laurate (20 mol%) was added.

With respect to the silylformylation (silylformylation)^[14] of unsaturated C–C bonds, Matsuda et al. reported a rhodium-catalyzed reaction of alkynes employing hydrosilanes under CO pressure [Eq. (2)].^[14a,b] Intramolecular alkene silylformy-



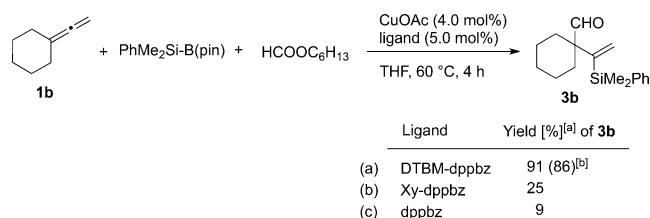


Scheme 2. Derivatization of a boraformylation product.

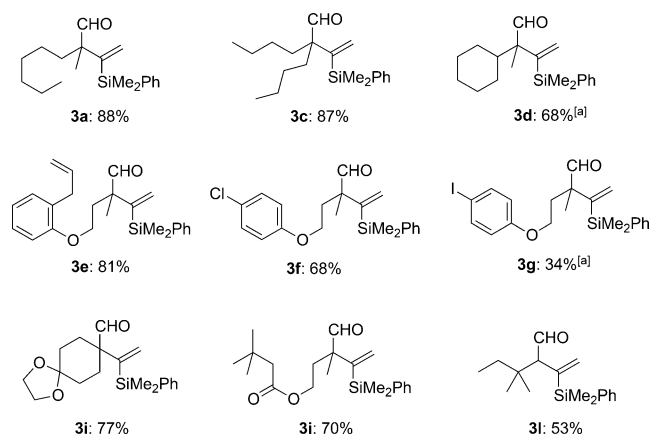
lation also proceeds under CO pressure (1000 psi).^[14h] However, there is no precedent for allene silylaformylation. The silylaformylation of allenes was found to proceed with a silylborane and a formate ester as silyl and formyl source, respectively, in the presence of a copper catalyst (Scheme 1b). Note that toxic CO was not required in the present silylaformylation. When the reaction of **1b** with $PhMe_2Si-B(\text{pin})$ and hexyl formate was conducted in THF at 60 °C, the silylaformylation product (**3b**) was obtained in 91 % GC yield and isolated in 86 % yield (Scheme 3a). Less bulky ligands such as *Xy*-dppbz and dppbz were not effective (Scheme 3b,c), which is in good agreement with the ligand effect observed in the boraformylation (Table 1).

Various allenes gave the corresponding β -silyl β,γ -unsaturated aldehydes in good to high yields via the silylaformylation reaction (Scheme 4). Functional groups, such as terminal olefin (**3e**), chlorophenyl (**3f**), iodophenyl (**3g**), acetal (**3i**), and ester (**3j**) moieties, were tolerated in the reaction. The monosubstituted allene **11** yielded the corresponding silylaformylation product (**31**) in moderate yield. Gram-scale silylaformylation of **1b** (4.0 mmol) was also possible and provided **3b** (1.0 g) in 95 % yield.

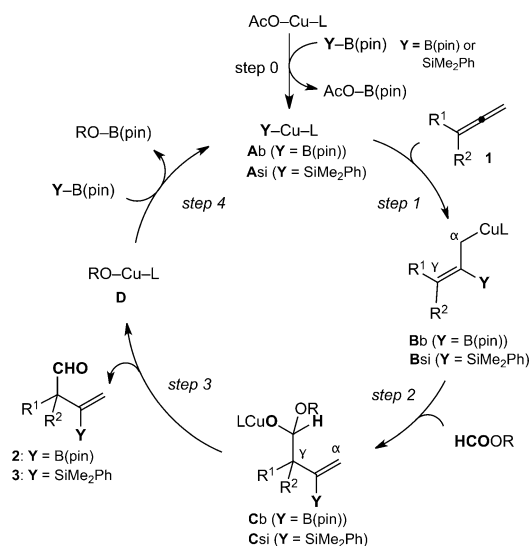
The bora- and silylaformylation reactions follow similar catalytic cycles (Scheme 5). It is known that boryl copper species (**Ab**) are generated by the reaction of $B_2(\text{pin})_2$ with Cu compounds.^[15] Silyl copper species (**Asi**) are also afforded upon reaction of $PhMe_2Si-B(\text{pin})$ with copper compounds.^[16] Thus **Ab** and **Asi** must be key catalyst species involved in the



Scheme 3. The effect of ligands on the silylaformylation. Reaction conditions: Reaction conditions: **1b** (0.20 mmol), $PhMe_2Si-B(\text{pin})$ (0.24 mmol, 1.2 equiv), hexyl formate (0.22 mmol, 1.1 equiv), CuOAc (4.0 mol%), ligand (5.0 mol%), THF (0.20 mL), 60 °C, 4 h. [a] Determined by GC analysis. [b] Yield of isolated product.



Scheme 4. Silylaformylation of various allenes. Reaction conditions: **1** (0.20 mmol), $PhMe_2Si-B(\text{pin})$ (0.24 mmol), hexyl formate (0.22 mmol), CuOAc (4.0 mol%), DTBM-dppbz (5.0 mol%), THF (0.20 mL), 60 °C, 4 h. Yields of isolated products are given. [a] 15 h.



Scheme 5. Possible catalytic cycle.

catalytic cycles (step 0). **Ab** and **Asi** subsequently add across the terminal double bond of an allene (**1**), generating β -boryl (**Bb**)^[17] or β -silyl (**Bsi**)^[18] allyl copper intermediates (step 1). Next, **Bb** and **Bsi** react with a formate ester at the γ -position to provide **Cb** and **Csi** via a six-membered-ring transition state

(step 2). β -Elimination from **Cb** and **Csi** produces **2** ($Y = B(\text{pin})$) and **3** ($Y = \text{SiMe}_2\text{Ph}$), which extrude alkoxy copper species **D** (step 3). It has been reported that ketone-s, ^[17e,18b] aldehydes, ^[17e,18b,d] and imines ^[17f,g] react with **Bb** and **Bsi** to give the corresponding allylated alcohols and amines. In the present reaction, the alkoxy moiety of the formate is efficiently removed as an alkoxy copper species (**D**) by copper species bearing rather bulky ligands, such as DTBM-dppbz and DTB-dppbz. Finally, σ -bond metathesis of **D** with $B_2(\text{pin})_2$ and $\text{PhMe}_2\text{Si}-B(\text{pin})$ regenerates the active catalyst species **Ab** and **Asi**, respectively (step 4).

In conclusion, bora- and silaformylation reactions of allenes have been described for the first time. For the boraformylation, $B_2(\text{pin})_2$ and formate esters were good boron and formyl sources, respectively, in the presence of a copper catalyst. The corresponding β -boryl β,γ -unsaturated aldehydes were selectively obtained in good to high yields. In the silaformylation, β -silyl β,γ -unsaturated aldehydes were provided when $\text{PhMe}_2\text{Si}-B(\text{pin})$ was employed as the silicon source in combination with a formate ester. Further studies on the reaction mechanisms and enantioselective variants are in progress.

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Conflict of interest

The authors declare no conflict of interest.

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