ORGANOMETALLICS

pubs.acs.org/Organometallics

Article

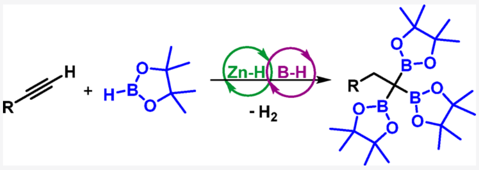
A Comparison of Two Zinc Hydride Catalysts for Terminal Alkyne C−H Borylation/Hydroboration and the Formation of 1,1,1-Triborylalkanes by Tandem Catalysis Using Zn−H and B−H Compounds

Marina Uzelac, Kang Yuan, and Michael J. Ingleson*

Cite This: https://dx.doi.org/10.1021/acs.organomet.0c00086

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: The synthesis of 1,1,1-triborylalkanes from terminal alkynes and pinacolborane (HBPin) is reported. This transformation proceeds via initial Zn-catalyzed alkyne C−H borylation, which can be achieved using a NacNacZnH complex. Combinations of a NacNacZn-alkynyl formed via C−H zincation of a terminal alkyne and HBPin exist in equilibrium with the alkynyl-BPin and NacNacZnH. The consumption of NacNacZnH by irreversible reaction with a terminal alkyne evolving H_2 is essential for driving alkyne C−H borylation to completion. The alkynyl-BPin compounds undergo hydroboration catalyzed by Zn−H complexes at raised temperatures with a {7DIPP}ZnH(NTf_2) complex (7DIPP = 1,3-bis(2,6-diisopropylphenyl)-4,5,6,7-tetrahydro-1*H*-1,3-diazepin-3-ium-2-ide) a more active catalyst for hydroboration than a NacNacZnH complex. Calculations indicate the {7DIPP}Zn−H congener has a more pronounced biphilic character than that of NacNacZnH (greater electrophilicity at Zn while maintaining a basic hydride). Of the two hydroboration steps, the hydroboration of alkynylBPin is catalyzed by Zn−H complexes, while the hydroboration of 1,1-diborylalkenes is catalyzed more effectively by B−H-containing species, including boranes formed in situ from HBPin. These observations led to a one-pot protocol being developed for converting terminal alkynes into 1,1,1-triborylalkanes that utilizes {7DIPP}ZnPh(NTf_2) as a precatalyst for the formation of 1,1-diborylated alkenes with subsequent addition of BH_3-THF as catalyst for the final step.

INTRODUCTION

Organoboron compounds have become staple reagents in chemical synthesis as they possess a desirable balance between stability and facile transformation into other functional groups.[1] Multiply borylated organic compounds embody especially attractive reagents because of the potential for the stepwise, selective conversion of the boryl groups into C−C and C-heteroatom bonds.[2] While compounds such as geminal bisboryl-alkanes have been extensively utilized in synthetic endeavors,[3] 1,1,1-triboryl alkanes have received much less attention. This is partly due to the greater complexity of making these compounds selectively and efficiently, a challenge that only recently has begun to be addressed. While the first selective route to 1,1,1-triborylalkanes is over 40 years old this multiple boronation of alkyl halides required excess lithium metal.[4] Recently, more efficient routes to 1,1,1-triborylalkanes have been achieved using transition metal catalysis. For example, Ir catalyzed C(sp^3)−H triborylation of 2-ethylpyridines,[5] and Ni catalyzed triborylation of benzylic C−H bonds.[6] Styrenes are also effective precursors to 1,1,1-triborylalkanes via Co-catalyzed borylation/hydroboration of vinylarenes[7] and Rh-catalyzed borylation/hydroboration of (*E*)-styrylboronates.[8] Nonetheless, general routes to 1,1,1-triborylalkanes using simple hydrocarbon starting materials and inexpensive, low-toxicity earth-abundant-metal-based catalysts are desirable for the wider uptake of these compounds in synthesis.

Terminal alkynes are attractive precursors to 1,1,1-triborylated alkanes as they are readily available inexpensive feedstocks. In this area, Chirik et al. utilized two different cobalt catalysts (Figure 1, top) to afford triborylated alkanes by first performing the 1,1-diboration of terminal alkynes with bis(pinacolato)diboron (B_2Pin_2) followed by hydroboration with pinacolborane (HBPin).[9] While notable work, cobalt has low permitted daily exposure (PDE) limits thus catalysts based on earth-abundant 3d metals with much less stringent PDE values, such as Fe, Cu, or Zn would be preferable.[10] During the course of this study, Marder et al. reported a Cu-based catalyst capable of the 1,1,1-triborylation of terminal alkynes in the presence of stoichiometric KF. This work (Figure 1b) represents a highly efficient method to access these

Received: February 7, 2020

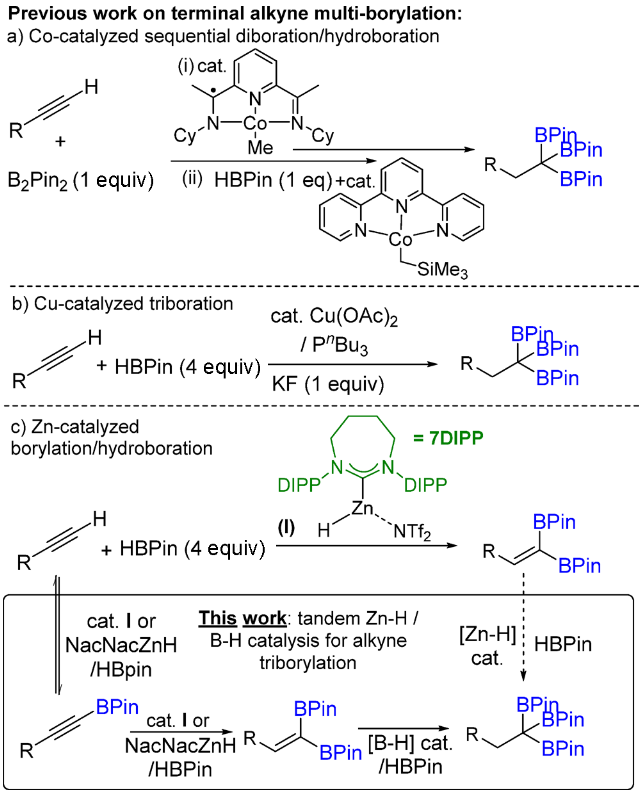
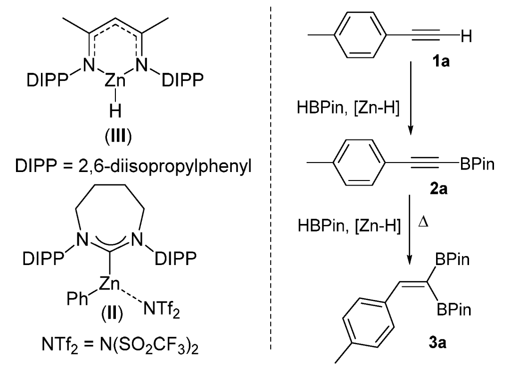


Figure 1. Select previous work. Inset this work on tandem Zn−H/B−H catalysis for forming 1,1,1-triborylated alkanes.

Scheme 1. Stepwise Transformation of Terminal Alkynes into 1,1-Diborylated Alkenes Using Zn−H III and Precatalyst II which Forms I In Situ on Metathesis with HBPin



compounds using a low toxicity and earth abundant metal based catalyst.[11]

There is an increasing interest in using zinc complexes as borylation catalysts,[12] and recently we demonstrated that a NHC-Zn complex {7DIPP}ZnH(NTf$_2$) (**I**, Figure 1c) or its precursor, {7DIPP}ZnPh(NTf$_2$) (**II**), is capable of catalyzing both the C−H borylation of terminal alkynes and the hydroboration of the alkynylBPin product affording 1,1-diborylated alkenes. In this work, the hydroboration step proceeded via alkyne hydrozincation then H−B/Zn−C metathesis.[13] Experimental findings supported by DFT calculations revealed that **I** contains a highly electrophilic zinc center and a hydridic (thus Brønsted basic) Zn−H moiety; thus, **I** is biphilic in character. Arguably the most well studied low-coordinate zinc hydride complexes use the *β*-diketiminate ligand (NacNac), with a *N*-DIPP substituted NacNac derivative enabling formation of a three coordinate zinc hydride, termed herein (DIPPNacNac)ZnH, **III** (Scheme 1, DIPPNacNac = $\{2,6\text{-}{}^{i}Pr_2H_3C_6N(CH_3)C\}_2CH$)).[14] While **III** and other low-coordinate zinc hydrides have been reported to catalyze the hydrosilylation and hydroboration of ketones and aldehydes, as well as the hydrosilylation of CO_2, **III** has to the best of our knowledge not been used to catalyze alkyne borylation.[15−17] Herein we report our studies comparing the reactivity of low-coordinate zinc hydride complexes **I** and **III** in the borylation of terminal alkynes. This led to the development of a tandem Zn−H/B−H catalytic system for the one-pot transformation of terminal alkynes into 1,1,1-triborylalkanes.

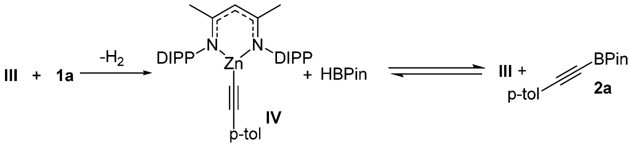
■ RESULTS AND DISCUSSION

Comparison of the Reactivity of Zn Catalysts. The reported 1,1-diboration of 4-ethynyltoluene (**1a**, right Scheme 1) with HBPin catalyzed by **I** or **II** (as a more readily accessible precatalyst), required heating to 90 °C for significant conversion of the alkynylBPin **2a** to **3a**.[13] Compound **III** was explored to determine if it was a more active catalyst than **I** in this transformation. However, from multiple attempts using **III** to catalyze the formation of **3a** from alkyne **1a**, it became evident that **III** is a less effective catalyst than **I**/**II** is for this conversion. This is illustrated by there being no observable formation of **3a** (by multinuclear NMR spectroscopy) after 25 h at 90 °C using 10 mol % of **III** in C_6D_6 (in a sealed tube). In contrast, using **I** under identical conditions **3a** is formed in good yield (and up to 73% yield after 36 h). Only when the reaction temperature is increased to 110 °C does **III** catalyze the formation of **3a** to any observable extent, albeit requiring 120 h at 110 °C to reach 90% conversion of **2a** to **3a**.

To explore the disparity between the two Zn−H catalysts we explored the initial step, formation of **2a** by C−H borylation. Comparing the activity of **III** to that of **I** for alkyne C−H borylation under identical conditions (1.1 equiv of HBPin, 10 mol % catalyst, 1 M THF solution, 60 °C) after only 120 min, 98% of **2a** was formed using **III**, making it faster than the borylation catalyzed by **I**. However, if the reaction is performed in C_6D_6, then **I** is slightly more active than **III** (though both are effective catalysts). We attribute this solvent disparity to the differing propensities of **I** and **III** to bind THF due to their relative electrophilicity (vide infra).

To gain further insight into the reactivity of **III**, stoichiometric reactions were performed. When **III** was reacted with terminal alkyne **1a** in a 1:1 ratio at room temperature in benzene, alkyne deprotonation takes place as evidenced by the consumption of the alkynyl $C{\equiv}C{-}H$ resonance in the ^1H NMR spectrum and concomitant formation of H_2 (δ_H = 4.47 ppm). The reaction affords a single major new (DIPPNacNac)Zn containing a product consistent with a (DIPPNacNac)Zn-(alkynyl) species (**IV**, Scheme 2).[18] The subsequent addition

Scheme 2. Deprotonation of Alkyne 1a by III and Reversible *σ*-Bond Metathesis between IV and HBPin



of 1 equiv of HBPin to **IV** resulted in formation of **2a**, as indicated by growth of a diagnostic resonance at 24.9 ppm in the ^{11}B NMR spectrum, and **III** concomitantly (indicated by the growth of the diagnostic Zn−*H* resonance at 4.37 ppm in the ^{1}H NMR spectrum). However, despite Zn−C_{sp}/H−BPin metathesis taking place at room temperature, this transformation does not go to completion (after 24 h at room temperature). This is not due to kinetic factors as after prolonged heating and then cooling back to room temperature the same ratio of **IV**: **2a** was observed, indicating an equilibrium process. As the equilibrium position was reached at room temperature, Zn−C/H−B metathesis proceeds with a relatively low barrier for this system. Consistent with this, combining **III** and **2a** in benzene led to a mixture containing **III**, **2a**, and the metathesis products HBPin and **IV** at room temperature confirming reversibility. This is comparable to previously reported reactivity observed on combining complex **I** with alkynylBPin species (where a σ-bond metathesis equilibrium was also observed). This suggests that reversible metathesis between Zn−H and (sp)C−B compounds with Δ*G* close to zero may be a common phenomenon for low-coordinate zinc complexes.

To further assess the relative reactivity of {7DIPP}Zn and NacNacZn systems calculations at the M06−2x/lanl2dz/6-311G/PCM(THF) level were performed. For the NacNacZn system, while alkyne deprotonation is thermodynamically favored (eq 1 in Figure 2), the metathesis of the resultant zinc-alkynyl species with HBPin is energetically uphill (eq 2 in Figure 2), albeit by <2 kcal mol^{-1}. Thus, the subsequent reaction of **III** with additional terminal alkyne is key to drive the reaction to completion and thus ensures high conversions to the alkynylBPin. Again, this is comparable with observations previously reported for the {7DIPP}Zn congener (see Figure 2 inset).

Comparison of the frontier molecular orbitals of [**I-THF**]$^+$ (see ref 19) and **III** indicated that as expected [**I-THF**]$^+$ is more electrophilic than **III**. The LUMO of [**I-THF**]$^+$ (Figure 2) has significant zinc character and at −0.74 eV is significantly lower in energy than the LUMO+1 of **III** (+0.46 eV) (the LUMO for **III** has no zinc contribution). However, the energy of the highest occupied molecular orbital with significant Zn−H character is comparable for both: For [**I-THF**]$^+$, it is the HOMO (−8.56 eV), and for **III**, it is the HOMO−5 (−8.50 eV). Also notably, comparison of the NBO charges of the Zn−H moiety in [**I-THF**]$^+$ and **III** found that the hydride in [**I-THF**]$^+$ has a magnitude of negative charge comparable to that of the hydride in **III** (−0.544 and −0.460, respectively). The positive charge on Zn is also comparable in [**I-THF**]$^+$ and **III** (+1.155 and +1.104, respectively). The energy of the key frontier orbitals and the charge distribution both support the hypothesis that low-coordinate {7DIPP}Zn−H cations combine considerable electrophilicity at zinc with a hydridic moiety. The more pronounced biphilic character (due to the lower LUMO energy) is possibly the key to the superior catalytic performance of **I** relative to **III**.

Formation of 1,1,1-Triborylated Alkanes. During the comparison of **I** and **III** in alkyne borylation, varying quantities of 1,1,1-triborylated alkane **4a** were observed at raised temperatures when using **I** (or **II**, e.g., Table 1, entries 1−3). No significant amount (<5%) of **4a** was observed in any reaction using **III** as the catalyst (even after 160 h at 110 °C in a sealed tube). Using precatalyst **II**, changing the solvent to other arenes such as toluene did not affect the outcome of this

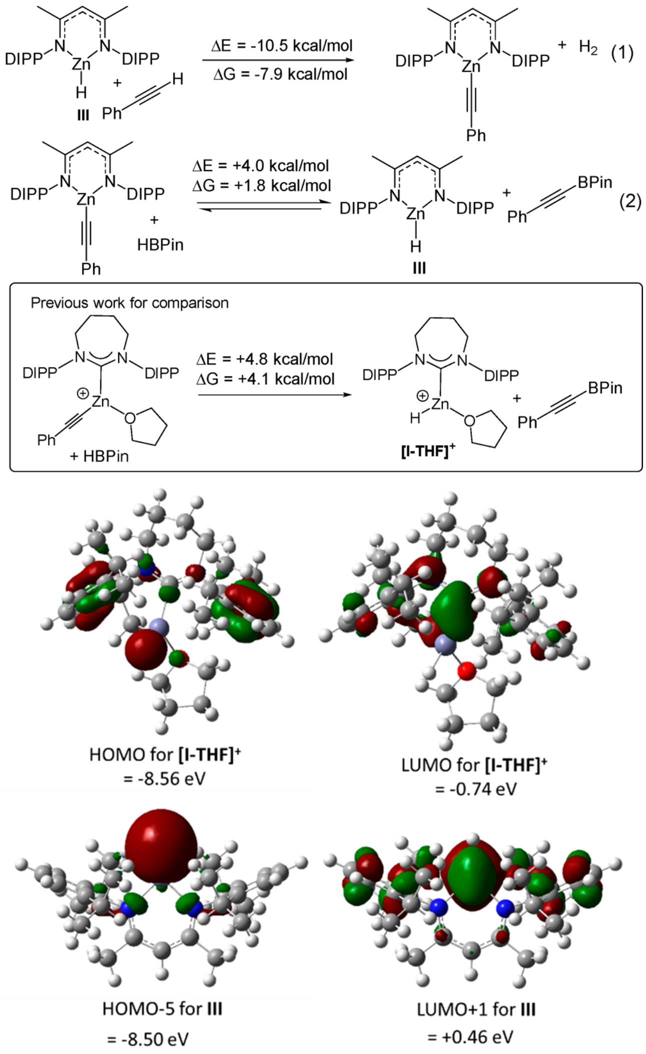
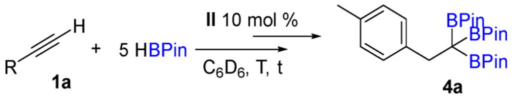


Figure 2. Top, the calculated energy changes for C−H zincation and for Zn−C/H−BPin metathesis for NacNacZn complexes and inset for comparison for NHC-Zn complexes.[13] Bottom, comparison of key select frontier molecular orbitals of **III** and [**I-THF**]$^+$ at isosurface value = 0.04.

Table 1. Optimization for Synthesis of 1,1,1-Triborylalkane[a]



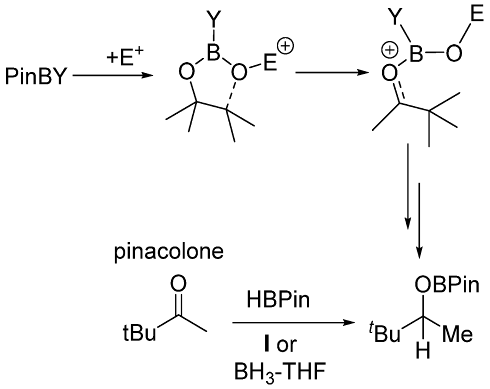
entry	*T* (°C)	conc [mol/L][e]	time [h]	**4a**[f]
1[b]	90	1	36	<1%
2	100	1	24	<5%
3	110	1	24	40
4[c]	110	1	24	46
5[d]	110	1	96	56
6	110	2	24	48
7	110	3	24	70

[a] Reaction conditions as shown unless otherwise indicated. [b] Using 4 equiv of HBPin, as in previous work (ref 13). [c] Using toluene instead of benzene. [d] Using 5 mol % of **I**. [e] Refers to the concentration of terminal alkyne **1a**. [f] Yields determined by in situ ^{1}H NMR spectroscopy vs CH_2Br_2 as an internal standard.

transformation significantly (entry 3 vs 4). Therefore, C_6D_6 was used purely to facilitate in situ reaction monitoring. Decreasing the catalyst loading had a detrimental effect while increasing the concentration helped to increase the yield (Table 1, entries 6–7). Despite some improvements, reactions required long times at high temperature to form a significant amount of **4a**, and unreacted diborylated alkene **3a** was observed in these reactions indicating incomplete conversion even after 24 h.

During reactions using **I** or **II**, significant HBPin decomposition was observed, with growth in ^{11}B resonances observed between 20 and 22 ppm consistent with $(RO)_3B$ species. Concomitantly, new H–B containing species were observed (as indicated by multiplets with $^1J_{B-H}$ couplings, including at −13 and −40 ppm in ^{11}B NMR spectra). It is feasible that under forcing conditions NHC dissociation from Zn is occurring,[13] and this Lewis base may facilitate degradation of HBPin.[20] However, an alternative decomposition pathway is also proceeding as indicated by formation of 2,2-dimethyl-3-OBPin-butane (Scheme 3), indicated by a diagnostic resonance at 3.95 ppm (q, $^3J_{HH}$ = 6.3 Hz).[21] This is presumably formed by electrophilic activation of a BPin species inducing a pinacol rearrangement (methyl migration, see Scheme 3) with subsequent hydroboration yielding the observed product, 2,2-dimethyl-3-OBPin-butane. Indeed, pinacolone was hydroborated to this product using HBPin under the reaction conditions catalyzed by **I** or BH3-THF (Scheme 3).

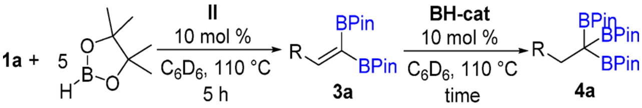
Scheme 3. Electrophile (E^+)-Initiated Formation of 2,2-Dimethyl-3-OBPin-butane



The extensive HBPin degradation observed in the presence of **I**/**II** at raised temperatures suggested that B–H species effective for catalyzing hydroboration may be formed in situ.[22] Analysis of the decomposition of HBPin during catalysis using precatalyst **II** at 60, 90, and 110 °C (see the Supporting Information) revealed that although formation of $(RO)_3B$ species and 2,2-dimethyl-3-OBPin-butane is observed at all three temperatures it takes much longer at the two lower temperatures. The same analysis also showed that the formation of **4a** (monitored using the characteristic $ArC\underline{H}_2$ resonance at 3.19 ppm) has an induction period (despite significant amounts of **3a** being present in solution after short reaction times at 110 °C). Together these observations suggested in situ formation of a B–H species that acts as a catalyst enabling formation of triborylated alkane **4a**. This borane is presumably formed by reaction of a {7DIPP}Zn species with HBPin as minimal HBPin degradation was observed in reactions using **III** under identical conditions. Thus, the disparity between the reactions using **I** and **III** is attributed to the absence of an in situ formed B–H catalyst[23] in reactions using (DIPPNacNac)Zn species due to the lower Lewis acidity of **III** relative to **I** (and derivatives).

Hydroboration of 1,1-Diborylalkenes by B–H-Containing Species. While THF-BH_3 was previously shown to be poor at catalyzing hydroboration of alkynylBPin **2a** to **3a** (particularly relative to **I**), we surmised that the increased steric bulk present in 1,1-diborylalkene **3a** afforded by the two BPin units may significantly disfavor hydrozincation of **3a** with sterically encumbered (7-DIPP)Zn–H species. Therefore, the ability of some common boranes to effect hydroboration of the 1,1-diborylated alkene **3a** to **4a** was explored (Table 2).

Table 2. Hydroboration of 1,1-Diborylalkene 3a Using Borane Catalysts[a]



entry	BH-cat	T (°C)	concentration	time [h]	4a[c]
1	BEt_3	110	3 M	24	37
2	$BH_3·SMe_2$	110	3 M	5	52
3[b]	$BH_3·SMe_2$	110	3 M	24	20
4	$BH_3·THF$	110	3 M	5	79
5	-	110	3 M	24	70

[a]Reaction conditions as shown unless otherwise indicated. [b]BH_3SMe_2 added after alkynylBPin (**2a**) formation instead of after formation of **3a**. [c]Yields determined by in situ ^1H NMR spectroscopy based on the ratio of product vs CH_2Br_2 added after the time shown as an internal standard.

BEt_3 was initially explored as it reacts in aromatic solvents with HBPin to form H_yBEt_x ($x + y = 3$) species, and we surmised that low steric bulk, base-free R_2BH/RBH_2 species may be required for catalyzing hydroboration of bulky **3a** via a mechanism related to that recently identified.[24] Substoichiometric amounts of BEt_3 were added to the standard reaction mixture (which still contains excess HBPin) after the formation of diborylated alkene **3a** using **I** (or **II**). This led to formation of EtBPin, H_yBEt_x ($x + y = 3$) species (by ^{11}B NMR spectroscopy) and desired product **4a**, albeit in modest yield (Table 2, entry 1). Next, guided by the work of Thomas, Cowley, and co-workers,[22] BH_3 compounds were explored and found to be more effective catalysts (entry 2). However, if BH_3 species were added earlier, specifically after formation of the alkynylBPin **2a** under otherwise identical conditions, then lower yields of 1,1,1-triborylalkane **4a** were obtained (compare entries 2 and 3). This is consistent with the importance of Zn–H in efficient formation of the diborylated alkene (**3a**) as previously discussed.[13] BH_3-THF proved the most effective catalyst when added post formation of the 1,1-diborylalkene (formed using **I** or **II**) with 10 mol % BH_3-THF affording desired product **4a** in much shorter reaction times and with higher yields than using just **I** or **II** (entry 4 vs 5).

With effective conditions for the synthesis of 1,1,1-triborylated alkanes (**4x**) from terminal alkynes identified using combined Zn–H/B–H catalysts, triborylation of a range of terminal alkynes was investigated. The substrates selected were determined by our previous report which documents the functional groups tolerated by species **I**/**II**.[13] Aromatic alkynes with both electron-donating and -withdrawing substituents were amenable providing desired products **4x** in moderate to good yields (Figure 3). It should be noted that electron-withdrawing substituents required slightly longer reaction times in the Zn-catalyzed transformation of terminal alkynes to diborylated alkenes consistent with our previous report.[13] Haloaryl-substituted alkynes were also tolerated, and no C−X (X = Br, Cl, and F) bond cleavage was detected. Furthermore, heteroaromatic and polyaromatic substrates such as 3-ethynylthiophene or 2-ethynylnaphthalene were suitable substrates for this methodology. However, in the case of 3-ethynylthiophene, despite prolonged heating only 30% of **4j** was obtained with significant amount of 1,1-diborylalkene **3j** remaining unreacted. Thus, the BH_3-catalyzed hydroboration is not efficient with this substrate. Furthermore, 1-ethynyl cyclohexene did not react to produce any significant amount (<10%) of triborylated product. It should be noted that for several of substrates in Figure 3 the omission of BH_3-THF was tested in the final step, but this led to lower yields of **4x** in all cases under otherwise identical conditions.

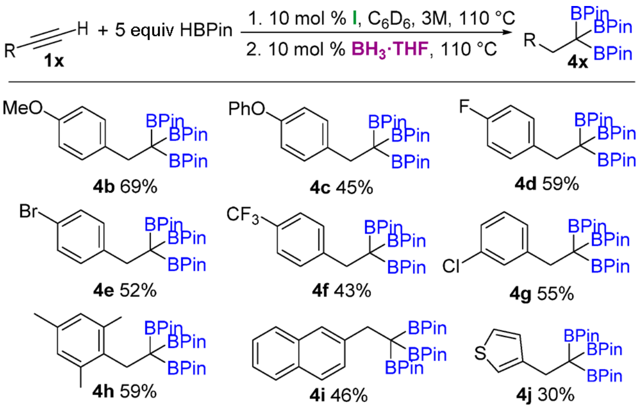
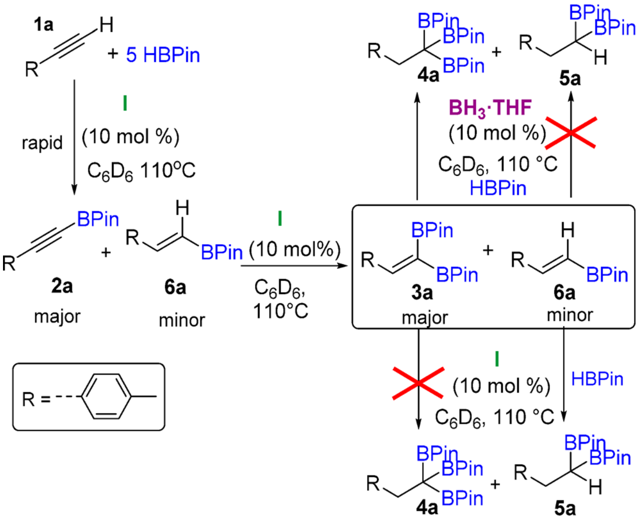


Figure 3. Scope of tandem Zn−H/B−H-catalyzed triborylation of terminal alkynes. Yields by in situ ^{1}H NMR spectroscopy vs CH_2Br_2 as internal standard.

The mass balance in these reactions was composed largely of a second borylated alkane product, **5x**, indicated by a diagnostic doublet ($^3J_{HH} \approx 8$ Hz) at ca. 2.7−2.9 ppm in the ^{1}H NMR spectra, consistent with a 1,1-diborylated alkane. The formation of **5x** (Scheme 4) is presumably via double hydroboration of the terminal alkyne as the 1,1,1-triborylated alkanes are stable under these reaction conditions (i.e., they do not undergo protodeboronation in situ). It was previously shown that in aromatic solvents while dehydrogenative borylation of **1x** to form **2x** dominates using **I** or **II** minor quantities of hydroboration products are observed (e.g., 2-[(*E*)-2-*p*-tolylethenyl]-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (**6a**)).[13] In situ analysis of the reaction starting from **1a** under standard conditions (110 °C, 3 M benzene solution, 5 equiv of HBPin, 10 mol % of **II**, sealed tube) revealed formation and then consumption of *E*-styrylboronate **6a**. Compound **6a** has an indicative resonance at 6.10 ppm (d, $^3J_{HH} = 18.3$ Hz) that is replaced by the appearance of a new doublet as the reaction proceeds at 2.87 ppm ($^3J_{HH} = 8.2$ Hz) consistent with **5a**.

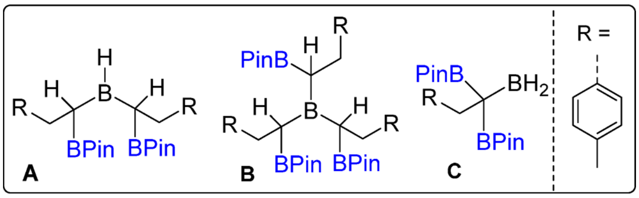
Identification of Catalytically Active Species. To determine the catalytically active species for the formation of **4a** and **5a**, compounds **3a** and **6a** were prepared independently. Adding 10 mol % BH_3-THF to **3a** and HBPin on heating (110 °C, 5 h) led to high-yield conversion to **4a**, confirming that a zinc species is not required for this step. In contrast, attempting the BH_3-THF-catalyzed hydroboration of **6a** afforded no detectable (by ^{1}H NMR spectroscopy) formation of **5a** (even at 110 °C). In contrast, compound **II** catalyzed production of **5a** from **6a** using HBPin (61% yield after 15 h at 110 °C). Thus, B−H species, such as BH_3-THF, are effective for the transformation of **3a** to **4a** but are ineffective for the transformation of **6a** to **5a**, with the opposite selectivity observed using **I**.

Scheme 4. Formation of 4a and 5a during Terminal Alkyne Borylation/Hydroboration Catalyzed by Zn−H and B−H Species



It was hypothesized that the failure of BH_3-THF to effect catalytic hydroboration of **6a** with HBPin is due to the reaction of BH_3-THF with multiple equivalents of **6a** to form sterically hindered compounds such as **A**/**B** (and isomers thereof, Scheme 5). Hindered R_3B compounds have been demonstrated to not undergo metathesis with HBPin;[24] thus, it is feasible that species like **A** or **B** would not react (or only react very slowly) with HBPin even on heating. The reaction of BH_3-THF with 2 equiv of **6a** in the absence of HBPin at ambient temperature led to a complex mixture, but key observations include the following: the complete consumption of **6a**; the formation of alkylBpin species (indicated by $\delta_{11B} = 34.1$ ppm); and the persistence of some BH_3-THF. Furthermore, these products did not react on further addition of HBPin and heating. This confirms a nonstoichiometric reaction occurs between **6a** and BH_3-THF to afford inactive (toward HBpin metathesis) organoboranes.

Scheme 5. Possible Products from the Reaction of BH_3-THF with 6a (A/B and Isomers Thereof) and 3a (C)[a]



[a]These compounds may also be THF adducts/hydride bridged dimers of **A**−**C**.

The number of equivalents of an alkene that a BH_3 species react with is highly dependent on alkene steric bulk. For example, Brown and co-workers showed that BH_3-THF and excess 2-methyl-2-butene proceeded rapidly to the dialkylborane product, while even with an excess of the more bulky alkene 2,3-dimethyl-2-butene the reaction only proceeded to the monoalkylborane product.[25] Thus, different alkene/BH_3-THF reaction ratios (and thus different degrees of sterics around boron and thus different barriers to metathesis with HBPin) may be the origin of the reactivity disparity between **3a** and **6a** with BH_3-THF. Consistent with this, combining 2 equiv of **3a** and BH_3-THF led to a rapid reaction but incomplete consumption of **3a** (indicating a 1:1 reaction stoichiometry) and the formation of a product consistent with **C**. On combination with HBPin, this reaction mixture yielded **4a** on heating. This indicates that the barrier to metathesis with HBPin for species dervied from **3a**/BH_3 (such as **C**) is significantly lower than that for species derived from **6a**/BH_3 (such as **A**/**B**). Thus, the ability of BH_3 species to catalyze hydroboration using HBPin is highly dependent on the steric bulk of the alkyne/alkene, which in turn controls the reaction stoichiometry between alkene/BH_3.

CONCLUSIONS

Direct comparison of {7DIPP}ZnH(NTf_2) (**I**) with a NacNacZnH (**III**) complex revealed that both can catalyze alkyne C−H borylation and alkyne hydroboration and that Zn−C(sp)/H−BPin metathesis was reversible for both. However, NacNacZnH (**III**) was a poorer catalyst for alkynylBPin hydroboration. This is attributed to the greater biphilic character of {7DIPP}ZnH species, which are more electrophilic than the NacNacZn congeners (based on the energy of the key zinc based unoccupied orbital) while still being hydridic. At raised temperatures {7DIPP}Zn species enabled the formation of 1,1,1-triborylated alkanes. However, this occurs after significant decomposition of HBPin, suggesting catalysis by in situ formed B−H species is key for the hydroboration of 1,1-diborylated alkenes in this case. Adding 10 mol % BH_3-THF after 1,1-diborylalkene formation led to more rapid formation of 1,1,1-triborylated alkanes in higher yield. This serves as another reminder of the potential for "Trojan horse"[23] hydroboration catalysis when using boranes such as HBPin. Notably, the ability of BH_3-THF to catalyze production of borylated alkanes by hydroboration/HBPin metathesis was found to be highly dependent on the substituents of the alkene. In this work, the bulkier alkene undergoes BH_3-catalyzed hydroboration with HBPin, while a less bulky alkene did not. This was attributed to differences in the alkene/BH_3 reaction stoichiometry leading to different intermediates (R_2BH vs RBH_2) that have significantly different steric environments around boron thus different barriers to metathesis with HBPin.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.organomet.0c00086.

Synthetic methods and characterization details (PDF)

Computed structures (XYZ)

AUTHOR INFORMATION

Corresponding Author

Michael J. Ingleson − *EastCHEM School of Chemistry, University of Edinburgh, Edinburgh EH9 3FJ, United Kingdom*; orcid.org/0000-0001-9975-8302;
Email: michael.ingleson@edinburgh.ac.uk

Authors

Marina Uzelac − *EastCHEM School of Chemistry, University of Edinburgh, Edinburgh EH9 3FJ, United Kingdom*; orcid.org/0000-0002-5060-7017
Kang Yuan − *EastCHEM School of Chemistry, University of Edinburgh, Edinburgh EH9 3FJ, United Kingdom*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.organomet.0c00086

Funding

European Research Council (769599).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was made possible by financial support from the Horizon 2020 Research and Innovation Program (grant no. 769599). Dr. Mark Crimmin is thanked for useful discussions and NacNacZnH.

REFERENCES

(1) (a) Miyaura, N.; Suzuki, A. Palladium-Catalyzed Cross-Coupling Reactions of Organoboron Compounds. *Chem. Rev.* **1995**, *95*, 2457−2483. (b) Hall, D., Ed. *Boronic Acids: Preparation and Applications*; Wiley-VCH, 2011.

(2) Rygus, J. P. G.; Crudden, C. M. Enantiospecific and Iterative Suzuki-Miyaura Cross-Couplings. *J. Am. Chem. Soc.* **2017**, *139*, 18124−18137.

(3) Miralles, N.; Maza, R. J.; Fernandez, E. Synthesis and Reactivity of 1,1-Diborylalkanes towards C−C Bond Formation and Related Mechanisms. *Adv. Synth. Catal.* **2018**, *360*, 1306−1327.

(4) (a) Castle, R. B.; Matteson, D. S. Methanetetraboronic and methanetriboronic esters. *J. Organomet. Chem.* **1969**, *20*, 19−28. (b) Matteson, D. S. Methanetetraboronic and Methanetriboronic Esters as Synthetic Intermediates. *Synthesis* **1975**, *1975*, 147−158.

(5) Mita, T.; Ikeda, Y.; Michigami, K.; Sato, Y. Iridium-catalyzed triple C(sp^3)−H borylations: construction of triborylated sp^3-carbon centers. *Chem. Commun.* **2013**, *49*, 5601−5603.

(6) Palmer, W. N.; Zarate, C.; Chirik, P. J. Benzyltriboronates: Building Blocks for Diastereoselective Carbon−Carbon Bond Formation. *J. Am. Chem. Soc.* **2017**, *139*, 2589−2592.

(7) Zhang, L.; Huang, Z. Synthesis of 1,1,1-Tris(boronates) from Vinylarenes by Co-Catalyzed Dehydrogenative Borylations−Hydroboration. *J. Am. Chem. Soc.* **2015**, *137*, 15600−15603.

(8) Baker, R. T.; Nguyen, P.; Marder, T. B.; Westcott, S. A. Transition Metal Catalyzed Diboration of Vinylarenes. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1336−1338.

(9) Krautwald, S.; Bezdek, M. J.; Chirik, P. J. Cobalt-Catalyzed 1,1-Diboration of Terminal Alkynes: Scope, Mechanism, and Synthetic Applications. *J. Am. Chem. Soc.* **2017**, *139*, 3868−3875.

(10) For toxicity classification/limits set by the European Medicines Agency, see https://www.ema.europa.eu/documents/scientific-guideline/international-conference-harmonisation-technical-requirements-registration-pharmaceuticals-human-use_en-21.pdf.

(11) Liu, X.; Ming, W.; Zhang, Y.; Friedrich, A.; Marder, T. B. Copper-Catalyzed Triboration: Straightforward, Atom-Economical Synthesis of 1,1,1-Triborylalkanes from Terminal Alkynes and HBPin. *Angew. Chem., Int. Ed.* **2019**, *58*, 18923−18927.

(12) For select examples of zinc catalysis to form C−B bonds, see (a) Bose, S. K.; Fucke, K.; Liu, L.; Steel, P. G.; Marder, T. B. Zinc-Catalyzed Borylation of Primary, Secondary and Tertiary Alkyl Halides with Alkoxy Diboron Reagents at Room Temperature. *Angew. Chem., Int. Ed.* **2014**, *53*, 1799−1803. (b) Bose, S. K.; Marder, T. B. Efficient Synthesis of Aryl Boronates via Zinc-Catalyzed Cross-Coupling of Alkoxy Diboron Reagents with Aryl Halides at Room Temperature. *Org. Lett.* **2014**, *16*, 4562−4565. (c) Bose, S. K.; Deissenberger, A.; Eichhorn, A.; Steel, P. G.; Lin, Z.; Marder, T. B. Zinc-Catalyzed Dual C−X and C−H Borylation of Aryl Halides. *Angew. Chem., Int. Ed.* **2015**, *54*, 11843−11847. (d) Tsuchimoto, T.; Utsugi, H.; Sugiura, T.; Horio, S. Alkynylboranes: A Practical Approach by Zinc-Catalyzed Dehydrogenative Coupling of Terminal Alkynes with 1,8-Naphthalenediaminatoborane. *Adv. Synth. Catal.* **2015**, *357*, 77−82. (e) Mandal, S.; Mandal, S.; Geetharani, H. Zinc-Catalysed Hydroboration of Terminal and Internal Alkynes. *Chem. - Asian J.* **2019**, *14*, 4553−4556.

(13) Procter, R. J.; Uzelac, M.; Cid, J.; Rushworth, P. J.; Ingleson, M. J. Low coordinate NHC-Zinc-Hydride Complexes Catalyze Alkyne C−H Borylation and Hydroboration using Pinacolborane. *ACS Catal.* **2019**, *6*, 5760−5771.

(14) Spielmann, J.; Piesik, D.; Wittkamp, B.; Jansen, G.; Harder, S. Convenient synthesis and crystal structure of a monomeric zinc hydride complex with a three-coordinate metal center. *Chem. Commun.* **2009**, 3455−3456.

(15) (a) Boone, C.; Korobkov, I.; Nikonov, G. I. Unexpected Role of Zinc Hydride in Catalytic Hydrosilylation of Ketones and Nitriles. *ACS Catal.* **2013**, *3*, 2336−2340. (b) Lortie, J. L.; Dudding, T.; Gabidullin, B. M.; Nikonov, G. I. Zinc-Catalyzed Hydrosilylation and Hydroboration of N-Heterocycles. *ACS Catal.* **2017**, *7*, 8454−8459. For a review including zinc-catalyzed reactions, see (c) Revunova, K.; Nikonov, G. I. Main Group Catalyzed Reduction of Unsaturated Bonds. *Dalton Trans* **2015**, *44*, 840−866.

(16) (a) Dawkins, M. J. C.; Middleton, E.; Kefalidis, C. E.; Dange, D.; Juckel, M. M.; Maron, L.; Jones, C. Two-coordinate terminal zinc hydride complexes: synthesis, structure and preliminary reactivity studies. *Chem. Commun.* **2016**, *52*, 10490−10492. (b) Lummis, P. A.; Momeni, M. R.; Lui, M. W.; McDonald, R.; Ferguson, M. J.; Miskolzie, M.; Brown, A.; Rivard, E. Accessing Zinc Monohydride Cations through Coordinative Interactions. *Angew. Chem., Int. Ed.* **2014**, *53*, 9347−9351.

(17) (a) Feng, G.; Du, C.; Xiang, L.; del Rosal, I.; Li, G.; Leng, X.; Chen, E. Y.-X.; Maron, L.; Chen, Y. Side Arm Twist on Zn-Catalyzed Hydrosilylative Reduction of CO_2 to Formate and Methanol Equivalents with High Selectivity and Activity. *ACS Catal.* **2018**, *8*, 4710−4718. (b) Mukherjee, D.; Wiegand, A.-K; Spaniol, T. P.; Okuda, J. Zinc hydridotriphenylborates supported by a neutral macrocyclic polyamine. *Dalton Trans.* **2017**, *46*, 6183−6186.

(18) Prust, J.; Hohmeister, H.; Stasch, A.; Roesky, H. W.; Magull, J.; Alexopoulos, E.; Uson, I.; Schmidt, H.-G.; Noltemeyer, M. Synthesis and Structural Characterization of *β*-Diketoiminate Complexes Containing Three-Coordinate Zinc and Copper Atoms. *Eur. J. Inorg. Chem.* **2002**, *2002*, 2156−2162.

(19) The mono-THF solvate is used throughout for DFT calculations. For reactions performed in benzene, a THF solvate is clearly not feasible; however, the THF solvate still is used to simplify the calculations (if THF is replaced by NTf_2, then mono- and bidentate NTf_2 binding modes need to be considered).

(20) Westcott, S. A.; Blom, H. P.; Marder, T. B.; Baker, R. T.; Calabrese, J. C. Nucleophile promoted degradation of catecholborane: consequences for transition metal-catalyzed hydroborations. *Inorg. Chem.* **1993**, *32*, 2175−2182.

(21) Chong, C. C.; Hirao, H.; Kinjo, R. Metal-Free -Bond Metathesis in 1,3,2-Diazaphospholene-Catalyzed Hydroboration of Carbonyl Compounds. *Angew. Chem., Int. Ed.* **2015**, *54*, 190−194.

(22) (a) Ang, N. W. J.; Buettner, C. S.; Docherty, S.; Bismuto, A.; Carney, J. R.; Docherty, J. H.; Cowley, M. J.; Thomas, S. P. Borane-Catalysed Hydroboration of Alkynes and Alkenes. *Synthesis* **2018**, *50*, 803−808. (b) Docherty, J.; Nicholson, K.; Dominey, A. P.; Thomas, S. A Boron−Boron Double Transborylation Strategy for the Synthesis of gem-Diborylalkanes. *ACS Catal.* **2020**, *10*, 4686−4691.

(23) For precedence on main group hydrides generating B−H species active for hydroboration catalysis, see Harder, S.; Spielmann, J. Calcium-mediated hydroboration of alkenes: "Trojan horse" or "true" catalysis? *J. Organomet. Chem.* **2012**, *698*, 7−14.

(24) (a) Shirakawa, K.; Arase, A.; Hoshi, M. Preparation of (*E*)-1-Alkenylboronic Acid Pinacol Esters via Transfer of Alkenyl Group from Boron to Boron. *Synthesis* **2004**, *2004*, 1814−1820. (b) Nieto-Sepulveda, E.; Bage, A. D.; Evans, L. A.; Hunt, T. A.; Leach, A. G.; Thomas, S. P.; Lloyd-Jones, G. C. Kinetics and Mechanism of the Arase-Hoshi R_2BH-Catalyzed Alkyne Hydroboration: Alkenylboronate Generation via B−H/C−B Metathesis. *J. Am. Chem. Soc.* **2019**, *141*, 18600−18611.

(25) (a) Schwier, J. R.; Brown, H. C. Hydroboration. 89. Preparation of Diborane, a sterically hindered monoalkylborane. Comparison with thexylborane. *J. Org. Chem.* **1993**, *58*, 1546−1552. (b) Brown, H. C., Zaidlewicz, M., Eds. *Organic Synthesis via Boranes*; Aldrich Chemical Company, 2001; Vol. *2*.