Experimental Section

All experiments were carried out under argon with the exclusion of air and moisture in Schlenk tubes sealed by Teflon stopcocks. The chemicals used were dried and purified according to the standard procedures and stored under argon. $[Cp_2TiMe_2]$ was synthesized according to ref. [8]. All the products were identified by comparison with authentic samples (^1H NMR, MS, TLC). PE: light petroleum (b.p. 40–60°C), EA: ethyl acetate.

Reaction of **1a** with **2a**: Alkyne **1a** (513 mg, 2.88 mmol) and amine **2a** (224 mg, 2.40 mmol) were dissolved in toluene (2.0 mL) under argon. After addition of a solution of $[Cp_2TiMe_2]$ (0.48 mL, 0.15 molL^{-1}, 0.072 mmol, 3.0 mol%) in toluene the mixture was heated at 100°C for 72 h in a closed Schlenk tube.

a) Isolation of the imine **3a**: The dark brown reaction solution was concentrated under vacuum. The residue was taken up in the minimum amount of methanol and then filtered. The light yellow fitrate was cooled to −30°C, and light yellow crystals of **3a** precipitated. Yield: 341 mg (1.26 mmol, 52%).

b) Isolation of the ketone **4a**: The reaction solution was treated with CH_2Cl_2 (10 mL) and silica gel (4.0 g). The mixture was stirred for 2 h at room temperature and then filtered. The filtrate was then concentrated on a rotary evaporator and the residue was purified by column chromatography on silica gel (PE:EA, 10:1) to give **4a**. Yield: 432 mg (2.20 mmol, 92%).

c) Isolation of the amine **5a**: At 0°C, the reaction solution was carefully added to a suspension of $LiAlH_4$ (137 mg, 3.61 mmol) in THF (10 mL) and the mixture was refluxed for 3 h. After cooling to 0°C, the excess $LiAlH_4$ was hydrolyzed with iced water and the precipitate was dissolved by dropwise addition of NaOH (2.0 M). The mixture was then extracted three times with CH_2Cl_2. The combined organic phases were washed with water, dried ($MgSO_4$), and concentrated on a rotary evaporator. Column chromatography of the residue on silica gel (PE:EA, 10:1) gave **5a**. Yield: 406 mg (1.49 mmol, 62%).

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Catalytic, Regiospecific End-Functionalization of Alkanes: Rhenium-Catalyzed Borylation under Photochemical Conditions**

Huiyuan Chen and John F. Hartwig*

The end-functionalization of alkanes remains an important, unsolved problem in chemistry.[1, 2] Although C–H bond activation by transition metals has been known for decades, there are few reactions that selectively functionalize alkanes using catalytic amounts of transition metals. For example, metal-catalyzed oxidations are notoriously unselective with linear alkanes.[3, 4] Photochemical carbonylations can give high, but not exclusive, selectivity for terminal products when catalyzed by $[RhCl(CO)(PMe_3)_2]$,[5, 6] and the product yields are limited by unfavorable thermodynamics.[5] Most recently, terminal olefins have been generated as the dominant product of dehydrogenation with a sacrificial hydrogen acceptor at early reaction times,[7] but this chemistry provides mixtures of alkenes at high conversions in the absence of acceptor.[8, 9]

We have previously reported that monoboryl complexes of tungsten functionalize alkanes stoichiometrically.[10] Regeneration of the boryl complex from the accompanying metal hydride and dimeric metal carbonyl products in this system requires several steps and external reagents, which prohibits catalytic functionalization. Thus, we have sought a related but alternative approach to catalytic borylation of alkanes. We report here a rhenium-catalyzed process that produces terminal organoborane products from alkanes and 4,4,4′,4′,5,5,5′,5′-octamethyl-2,2′-bi-1,3,2-dioxaborolane (B_2pin_2) under photochemical conditions. Organoboranes are established, versatile synthetic intermediates that can be converted into alcohols, amines, halocarbons, aldehydes, and alkylarenes without loss of regiochemistry.[11]

Our initial studies employed stoichiometric amounts of $[Cp'M(CO)_3]$ (**1**: $Cp' = C_5H_4Me$, M = Mn; **2**: $Cp' = C_5H_5$, M = Re; **3**: $Cp' = C_5Me_5$ (Cp^*), M = Re) to determine whether alkane functionalization would occur with these complexes and whether the reaction would consume the starting complex or regenerate it to allow for catalysis. Irradiation of B_2pin_2 alone in neat pentane with a 450-Watt medium-pressure Hanovia mercury arc lamp gave no reaction, but irradiation of B_2pin_2 in the presence of complexes **1**, **2**, or **3** produced 1-pentylboronate ester **4** (Scheme 1), the product of alkane functionalization in the terminal position.[12] HBpin, which decayed to $(Bpin)_2(\mu\text{-}O)$ during the reaction, was the accompanying product. Yields of HBpin were determined by addition of benzaldehyde to form the pinacol benzyloxyl-

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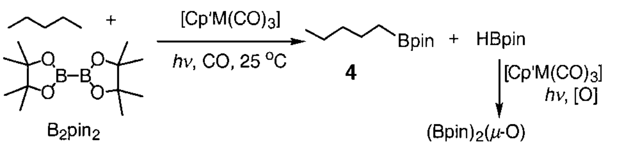
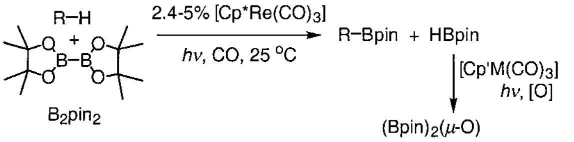


Scheme 1. Stoichiometric reaction of B_2pin_2 with $[Cp'M(CO)_3]$ in pentane. $Cp' = C_5H_5$, C_5H_4Me, C_5Me_5; M = Mn, Re.

borate, which was quantified by ^{1}H NMR spectrometry. Although the formation of **4** from these reactions was encouraging, the functionalized product was produced in only 35% yield for reactions with manganese complex **1** and in 50% yield for those with rhenium complex **2**. Reactions using Cp* complex **3** produced **4** in quantitative yields, but only 17% of the rhenium complex was regenerated.

The presumed $[Cp^*Re(CO)_n]$ intermediates that would result from extrusion of the borane products are known to form stable bridging carbonyl dimers.[13] Thus, we conducted reactions under CO in hopes of regenerating $[Cp^*Re(CO)_3]$ instead of forming catalytically inactive species. Indeed, irradiation of B_2pin_2 in pentane under 2 atm of CO in the presence of 2.4 mol% of **3** produced **4** in 95% yield (NMR spectroscopy; isolated in 65% yield; Scheme 2, $R = n\text{-}C_5H_{11}$).[12a] Entries 1–3 of Table 1 show the results for reactions of B_2pin_2 with a variety of alkanes catalyzed by $[Cp^*Re(CO)_3]$ to produce primary alkylboronate esters. In the absence of added CO, the reaction of B_2pin_2 in pentane with 5% $[Cp^*Re(CO)_3]$ produced **4** in only 22% yield; 72% of the B_2pin_2 remained, and all of the catalyst had been consumed.



Scheme 2. Reaction of B_2pin_2 in pentane catalyzed by $[Cp^*Re(CO)_3]$. $Cp' = C_5H_5$, C_5H_4Me, C_5Me_5; M = Mn, Re; $R = n\text{-}C_5H_{11}$, $i\text{-}C_5H_{11}$, $CH_2C_6H_{11}$.

Table 1. Regiospecific, catalytic functionalization of alkanes, alkyl ethers, and benzene.[a]

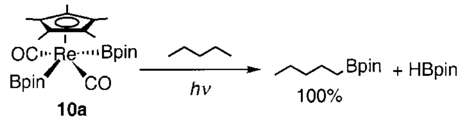
Entry	Substrate	Catalyst (amount [%])	t [h]	Conv. of B_2pin_2 [%]	Yield [%] RBpin	Yield [%] HBpin
1	*n*-pentane	**3** (2.4)	56	94	95 (**4**)	32
2	2-methylbutane	**3** (3.4)	55	89	83[b]	24
3	methylcyclohexane	**3** (5.0)	60	88	75 (**6**)	27
4	di-*n*-butyl ether	**3** (5.0)	45	100	100 (**7**)	23
5	*tert*-butyl ethyl ether	**3** (4.9)	46	100	82 (**8**)	26
6	benzene	**1** (10)	36	97	76 (**9**)	23
7	*n*-pentane	**10a** (2.5)	56	92	97 (**4**)	31

[a] A solution in pentane containing $[Cp^*Re(CO)_3]$, dodecahydrotriphenylene (internal standard), B_2pin_2, and CO (2 atm) was irradiated with a Hanovia medium-pressure mercury arc lamp. Yields were determined by GC or ^{1}H NMR spectroscopy, and yields of isolated products were determined after purification by chromatography on silica gel eluting with pentane or pentane/diethyl ether. [b] The two terminal regioisomers **5a** and **5b** were obtained in a 3.6:1 ratio.

All reactions of B_2pin_2 with alkanes were remarkable in their regiospecificity for the functionalization of primary sites. Reaction with pentane produced a single functionalized product **4**. None of the internal isomers, which were prepared by independent synthesis, were detected by GC/MS. Reaction with isopentane also produced only terminal substitution products, 3-methyl-1-butylboronate ester (**5a**, 65%) and 2-methyl-1-butylboronate ester (**5b**, 18%).[14] Reaction with methylcyclohexane produced 1-cyclohexyl-1-methylboronate ester (**6**) in 75% yield. Some regioisomeric products were observed in this case, but taken together they constituted less than 1% yield. The low reactivity of these catalysts for secondary C–H bonds was underscored by the rhenium-catalyzed reaction of B_2pin_2 with cyclohexane, which gave no alkylboronate ester and only a trace amount of HBpin.

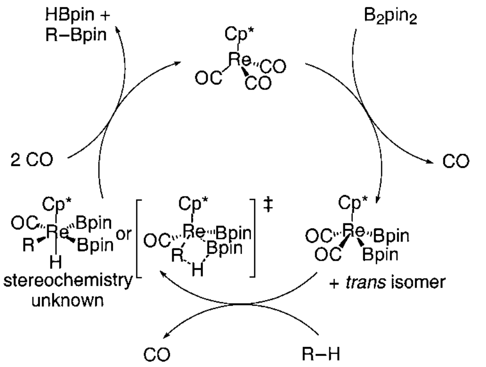
Ether substrates also underwent borylation at the termini of aliphatic substituents (Table 1, entries 4, 5). The photochemical reaction of B_2pin_2 in *n*-butyl ether with 5% catalyst produced the 4-butoxy-1-butylboronate ester **7** in quantitative yield (NMR spectrometry; isolated in 55% yield). A similar reaction with the unsymmetrical *tert*-butyl ethyl ether produced product **8** in 82% yield (NMR spectroscopy; isolated in 75% yield) from functionalization at the terminal position of the ethyl group. The selectivity toward other regioisomers was greater than 350:1. The reaction of benzene with B_2pin_2 was effectively catalyzed by manganese complex **1** under 2 atm of CO to form the phenylboronate ester **9** in good yield (Table 1, entry 6).

trans-$[Cp^*Re(CO)_2(Bpin)_2]$ (**10a**) was isolated from the reaction of B_2pin_2 with $[Cp^*Re(CO)_3]$ in cyclohexane; *cis*-$[Cp^*Re(CO)_2(Bpin)_2]$ (**10b**) was observed at early reaction times. Both pure **10a** and mixtures of the *cis* and *trans* isomers catalyzed the photochemical borylation of pentane in the same manner as $[Cp^*Re(CO)_3]$ (Table 1, entry 7). Moreover, the stoichiometric reaction of **10a** in pentane led to the regiospecific formation of boronate ester **4** in quantitative yield [Eq. (1)]. These results suggest that the reaction involves initial oxidative addition of the diboron compound followed by C–H activation and functionalization of the alkane (Scheme 3). After photochemically induced CO dissociation,[15] the C–H activation of pentane by **10a** or **10b** could occur by oxidative addition to generate a Re^V intermediate or by σ-bond metathesis involving Re^{III} (as shown in Scheme 3).[16] An alternative catalytic cycle could involve initial oxidative addition of the alkane and subsequent reaction of the alkylrhenium hydride with B_2pin_2. This pathway is not ruled out by our data, but is less likely considering the isolation of **10a** and **10b**, their conversion into the products of the catalytic process, and the known thermal instability of $[Cp^*Re(CO)_2(H)(CH_3)]$.[17]



(1)

Preliminary studies to determine the origin of the regiospecificity were conducted. Specifically, we probed for metal-catalyzed conversion of internal activation products into the



Scheme 3. Proposed mechanism for the photochemical reaction of B_2pin_2 with alkenes catalyzed by [Cp*Re(CO)$_3$].

more thermodynamically stable terminal products.[18] To do so, we added the pinacol ester of 2-butylboronic acid to the catalyzed reaction of B_2pin_2 with pentane. The 2-butylboronate ester remained unchanged during the formation of **4**, ruling out isomerization of products formed from initial functionalization of the secondary C–H bonds to end-functionalized products. Therefore, the terminal boronate esters are kinetic products, and the selective functionalization most likely results from a regiospecific reaction of the rhenium bis-boryl complex with the alkane primary C–H bond. Higher reactivity of primary over secondary C–H bonds has been observed in stoichiometric oxidative addition and σ-bond metatheses.[16, 19]

In summary, we report the regiospecific conversion of alkanes into linear alkylboronate esters, which are common and valuable synthetic intermediates. This chemistry provides the highest regioselectivity of any catalytic alkane functionalization we are aware of, including either enzymatic or synthetic catalyst systems.

Experimental Section

Typical procedure for the photochemical reaction of B_2pin_2 with hydrocarbon substrates catalyzed by [Cp*Re(CO)$_3$] or [(C$_5$H$_4$Me)Mn(CO)$_3$]: Preparation of **4:** A solution containing [Cp*Re(CO)$_3$] (2.6 mg, 0.0064 mmol), dodecahydrotriphenylene (internal standard, 4.5 mg, 0.019 mmol), and B_2pin_2 (66.5 mg, 0.262 mmol) in dry pentane was placed in an NMR tube. A small aliquot of the starting reaction mixture was removed to obtain initial GC and ^{1}H NMR spectral data before the tube was attached to a vacuum adapter. The solution in the NMR sample tube was frozen, the system was evacuated, and carbon monoxide (400 Torr) was introduced to the NMR tube at 77 K before the sample was flame-sealed. The solution was then irradiated for 56 h at ambient temperature, and the reaction was monitored by ^{11}B NMR spectroscopy. The sample was then opened in the glove box, and an aliquot was removed for GC and ^{1}H NMR analysis to determine the yields of alkylboronate ester. The yield of **4** determined by GC analysis was 95%. To determine the yield of pinacolborane, an aliquot of the final solution was combined with excess benzaldehyde in toluene and placed into an NMR tube. The solution was frozen, the system was evacuated, and the sample tube was flame-sealed before heating at 100 °C for 10 h. HBpin was quantitatively converted into pinacol benzyloxylborate, whose yield was determined by ^{1}H NMR spectroscopy (32% for the reaction of B_2pin_2 with pentane). Product **4** was isolated in 65% yield by chromatography on silica gel of a reaction mixture generated by a similar procedure using 5 mol% catalyst.

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