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Boron Recycling in the Metal-Free Transfer C-H Borylation of Terminal Alkynes and Heteroarenes

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Keywords: Metal-free catalysis • Transfer borylation • C-H activation • Boron recycling • Conjugate addition

Supporting Information Placeholder

ABSTRACT: Transfer C-H borylation is an isodesmic approach to the borylation reaction using B-C containing molecules as boron sources. In this work, we report that 2-mercaptothiazole and other analogues are active for the metal-free borylation of heterocycles and terminal alkynes. Alkynes are challenging substrates to C-H borylate since they undergo side-reactions with most borylating agents. The ability of these metal-free catalysts to activate B-C bonds can also be translated to the activation of B-O bonds in the products of the 1,4-conjugate addition of alkynylboranes to chalcones. It is therefore possible to prepare β-alkynylketones from the corresponding alkynes in a process where the boron source is used in sub-stoichiometric amounts. The mechanism and degradation patterns of these catalytic transformations have been investigated.

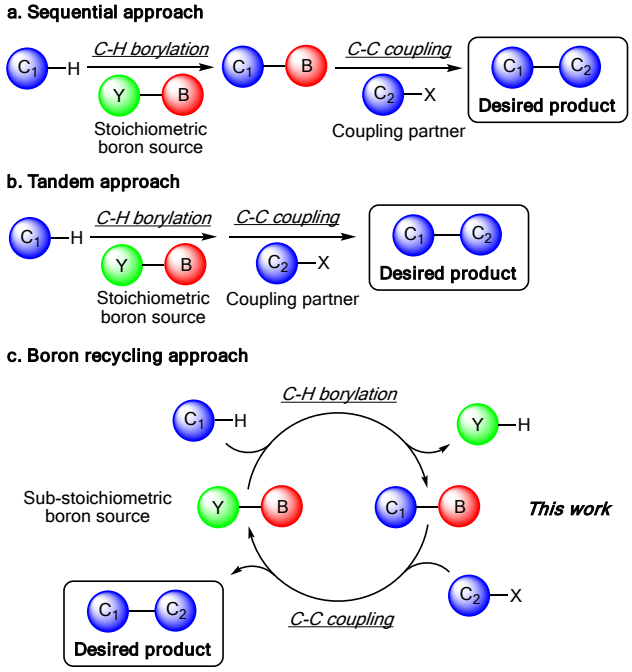
INTRODUCTION

The boron-carbon bond is a versatile functional group in synthetic chemistry. The ability to use alkyl- and arylboronates to create carbon-carbon bonds via Suzuki-Miyaura coupling[1] or carbon-heteroelement bonds via Chan-Evans-Lam coupling[2,3] makes them attractive substrates for the synthesis of fine chemicals.[4] Consequently, there is a significant interest in the development of methodologies to create boronate reagents. While several stoichiometric processes to borylate organic molecules exist,[5–8] usually involving strong bases, catalysis for the construction of B-C bonds is an appealing green alternative.[9] In these transformations, C-X[10–12] or C-H[9,13–16] bonds are activated to generate the desired molecules. However, the borane reagents of choice for these catalytic processes (hydroboranes or haloboranes) are air sensitive and show low tolerance to many functional groups. Diboron(4) compounds are also widely used,[10,17,18] but the generation of hydroboranes during catalytic cycles can be detrimental to catalysis by reacting with some important functional groups, notably those that are protic or that can undergo hydroboration reactions.[19] In addition, most of these systems are air and moisture sensitive and require anhydrous conditions to operate.

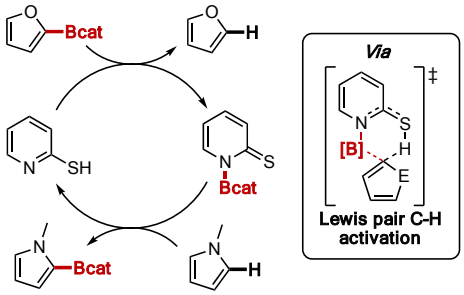
Although widely used, boronate functional groups are mostly considered sacrificial. Therefore, the high cost of these reagents can be problematic in large-scale processes where the production costs are high and the profit margins are low, such as in the agrochemical or modern materials industries. In an attempt to reduce synthetic steps, simpler methodologies such as tandem borylation/functionalization have been reported,[20–29] removing one isolation step by having one-pot reactions. While we have been looking at the design of cheap and metal-free catalysts for the C-H borylation[30–33] using the concept of FLP chemistry,[34–41] a topic of current interest in metal-free catalysis,[42–48] our current efforts are towards recycling the boronate moiety from the final products during C-H borylation tandem processes. In such a process, the borylation reagent could be used in catalytic amount (Scheme 1). Using a similar concept, Gellrich and collaborators recently reported a metal-free pyridonate borane catalyst for the dimerization of terminal alkynes.[49] Still, the development of this type of reaction is surprisingly stagnant.

We recently demonstrated that 2-mercaptopyridine could be used as a catalyst for the C-H borylation of heteroarenes using ArBcat as borylation agent (Ar = 2-furyl, 4-tolyl, 4-anisyl) by a mechanism illustrated in Scheme 2.[33] This reaction is based on the concept of isodesmic reactivity,[50] *aka* transfer borylation, which

allows using arylboronates as boron sources. The system showed good tolerance towards moisture and could tolerate functional groups that are usually problematic in C-H borylation methodologies, such as alkynes, alkenes and nitriles. However, it suffered from low TOF and TON and required high temperatures to operate. Herein, we report a new generation of robust catalysts for the transfer borylation of arenes and terminal alkynes. This system constitutes the first reported example of a metal-free catalyst for the C-H borylation of terminal alkynes. We also demonstrate that this approach can be used to recycle the boron moiety in tandem C-H borylation/functionalization reactions by performing 1,4 conjugate addition on chalcone derivatives. To our knowledge, this report is the first example of a C-H borylation reaction where the reaction requires only a sub-stoichiometric amount of borylation agent.



Scheme 1. Approaches to borylation/functionalization

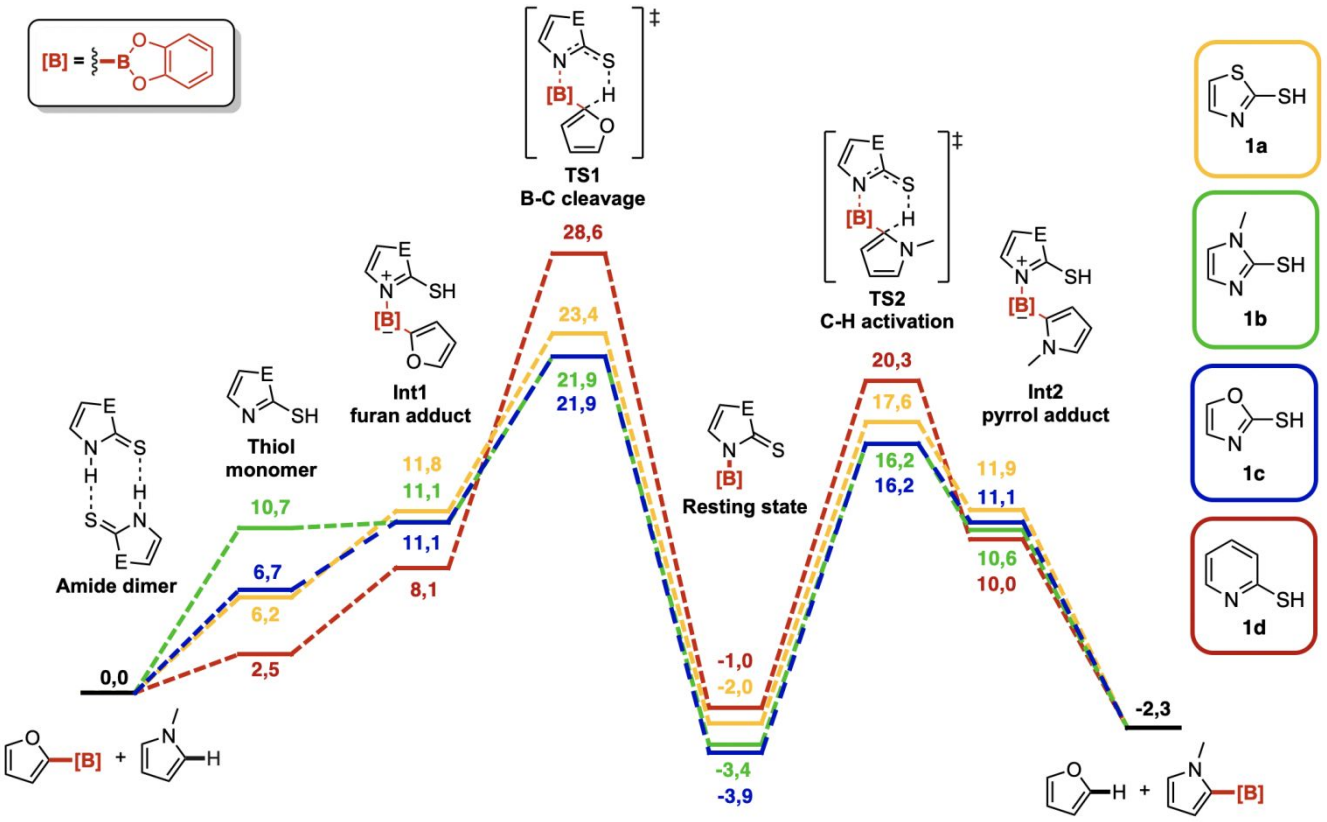


Scheme 2. Previously reported transfer C-H borylation using 2-mercaptopyridine as catalyst[33]

RESULTS

Catalyst design. While 2-mercaptopyridine proved to be a good catalyst for transfer borylation using 2-furylBcat (**2a**), it was less efficient when using 4-anisylBcat (**2b**), 4-tolylBcat (**2c**) and phenylBcat (**2d**), which are all less expensive and more practical borylation agents.[33,51] In order to cleave the strong B-C bond in the latter reagents, we sought to find more active catalysts that have both a Lewis base and Brönsted acid, such as in 2-mercaptopyridine (**1d**). Since modifying the electronic properties of the pyridine backbone did not yield significant change in reactivity, we investigated the impact of ring size on the reaction. We screened commercially available 5-membered rings 2-mercaptothiazole (**1a**), *N*-methyl-2-mercaptoimidazole (**1b**) and 2-mercaptooxazole (**1c**), first using computational chemistry.

As seen in Scheme 3, we optimized the intermediates and transition states using DFT (ωB97XD/def2-TZVP[52,53]). The important steps in this mechanism are the B-C bond cleavage of the arylboranate (**TS1**) and the C-H activation of the arene (**TS2**). Both processes are concerted and typical of FLP chemistry and no impactful borenium-type intermediates were observed. The energy barrier for the B-C bond cleavage, which is rate limiting in this catalytic process, is predicted to be lower with catalysts **1a-c** (21.9-23.4 kcal mol^{-1}) than with the 2-mercaptopyridine (28.6 kcal mol^{-1}). Interestingly, the energy required for the C-H activation from the resting state (about 20 kcal mol^{-1}) is similar in all systems.



Scheme 3. Gibbs free energies (ΔG) in kcal mol^{-1} of the intermediates and transition states for the borylation of N-methylpyrrole by catalysts 1a-1d calculated at DFT/ωB97XD/def2-TZVP level of theory.

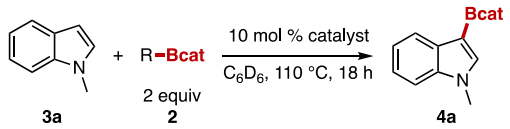
One hypothesis to explain the lower energy of the transition state for the B-C bond cleavage is the optimal geometry of the new catalysts. Indeed, 5-membered rings lead to a greater N-C-S angle than 6-membered rings (see Table 1). This change reduces the distortion in the transition state, making it more readily accessible. To verify this hypothesis, a strain-distortion/interaction model was used.[54] It allows to separate the electronic energies of a transition state $\Delta E^{\ddagger}$ in two factors: the distortion energies ($\Delta E_d^{\ddagger}$) and the interaction energies ($\Delta E_i^{\ddagger}$). $\Delta E_d^{\ddagger}$ corresponds to the energies required to bend the different components from their ground state to their geometry in the transition state and the $\Delta E_i^{\ddagger}$ corresponds to the electronic energies that stabilize that given state. As shown in Table 1, species **1a-c** have lower distortion energies (90.0, 97.6 and 88.7 kcal mol^{-1}, respectively) than **1d** (106.0 kcal mol^{-1}), indicating that the increased NCS angle is contributing to the decreased energy barrier.

Table 1. Distortion energies of catalysts 1a-d calculated at the DFT/ωB97XD/def2-TZVP level of theory.

Cat.	N-C-S_{angle}	$\Delta E^{\ddagger}$	$\Delta E_{d\ cat}^{\ddagger}$	$\Delta E_{d\ sub}^{\ddagger}$	$\Delta E_d^{\ddagger}$	$\Delta E_i^{\ddagger}$
	°	kcal mol^{-1}				
1a	124.8	17.7	42.6	47.4	90.0	-72.2
1b	126.3	16.7	48.2	49.6	97.6	-80.9
1c	125.8	16.6	43.4	45.3	88.7	-72.2
1d	118.2	21.9	52.1	53.9	106.0	-84.0

With these encouraging computational results in hand, we tested these candidates for the isodesmic C-H borylation of *N*-methylindole (**3a**). While all catalysts yielded quantitatively the C3-borylated product (**4a**) with 2-furylBcat (**2a**) in the specific conditions tested (see Table 2), the 5-membered ring catalysts **1a-c** exhibited significantly higher conversions with 4-anisylBcat (**2b**) and 4-tolylBcat (**2c**). 2-mercaptothoazole (**1a**) seemed to be the most efficient catalyst as it was able to convert **3a** to the 3-Bcat-*N*-methylindole (**4a**) with conversions of 42 % and 19 % with boron sources **2b** and **2c**, respectively.

Table 2. Borylation of *N*-methylindole with various boron sources.

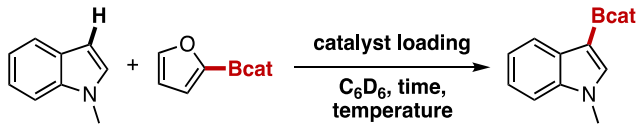


	1a	1b	1c	1d[a]
2a Bcat	> 95 %	> 95 %	> 95 %	> 95 %
2b Bcat	42 %	35 %	28 %	< 5 %
2c Bcat	19 %	15 %	10 %	< 5 %
2d Bcat	< 5%	< 5%	< 5%	0 %

[a] **Reactions carried out for 24 h at with 25 mol % catalyst loading and 5 equiv of the boron source.**

Borylation of arenes. Since 2-mercaptothiazole (**1a**) gave the best conversion with *N*-methylindole, it was chosen for further optimization (Table 3). By directly comparing with the catalytic activity of 2-mercaptopyridine (**1d**, Entry 12), **1a** was more reactive since we could reduce the catalyst loading from 25 % to 5 %, the excess of borylating agent from 5 equiv to 2 equiv and the reaction time from 24 h to 4 h and still reach over 95 % conversion (Entry 3). Alternatively, the reaction can be carried out at 80 °C overnight at the cost of higher catalyst loading (Entry 6). Interestingly, 26 % conversion was observed simply by leaving the reaction at ambient temperature overnight (Entry 11), which is expected for reactions having predicted energy barriers ranging from 21.9 to 23.4 kcal mol^{-1}. One hypothesis for the higher yields using elevated temperatures (80 °C or 110 °C) is that the removal of the volatile furan from the solution to the gas phase drives the thermodynamically controlled reaction to completion.

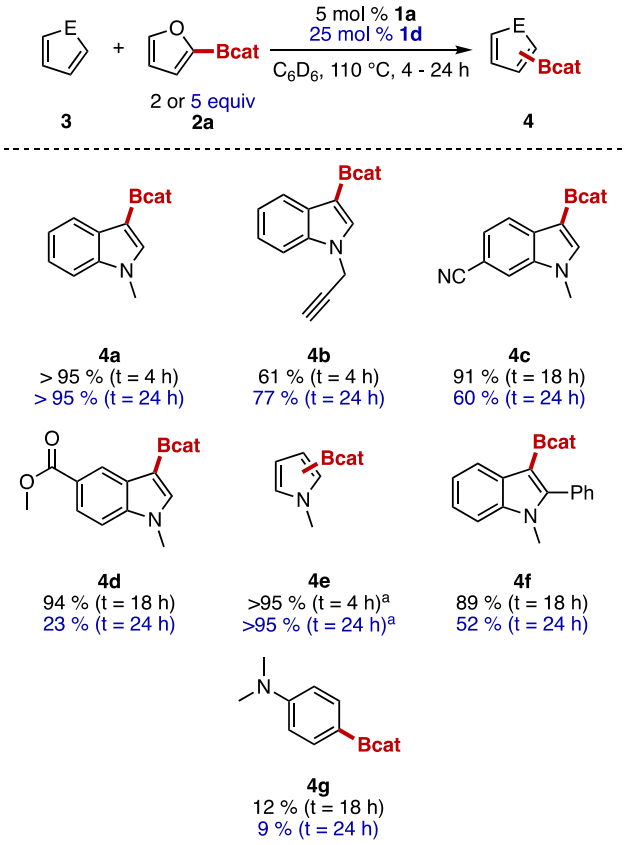
Table 3. Optimization of the borylation of *N*-methylindole.



Entry	Catalyst	2a	Temp	Time	Conv.[a]
	(mol %)	equiv	°C	h	%
1	**1a** (10)	2	110	18	> 95
2	**1a** (10)	2	110	4	> 95
3	**1a (5)**	**2**	**110**	**4**	**> 95**
4	**1a** (2)	2	110	4	93
5	**1a** (2)	2	110	18	> 95
6	**1a** (10)	2	80	18	> 95
7	**1a** (5)	2	80	18	89
8	**1a** (2)	2	80	18	82
10	**1a** (10)	2	50	18	54
11	**1a** (10)	2	20	18	26
12	**1d (5)**	**2**	**110**	**4**	**44**

[a] **Conversion obtained via ^{1}H NMR. Reactions were carried out in Teflon sealed NMR tube (J.-Young) with 0.15 mmol of substrate and a hexamethylbenzene internal standard.**

With these optimal conditions, **1a** proved more efficient than **1d** for the borylation of a large variety of substrates (**4a-4f**, Scheme 4). As expected, the system remains air and moisture stable and demonstrates a good tolerance and selectivity towards esters, alkynes and nitriles. Although the increase in reactivity with **1a** is notable compared to our previous report, the borylation of *N,N*-dimethylaniline (**4g**) remains challenging, with only 12 % conversion after 18 h.

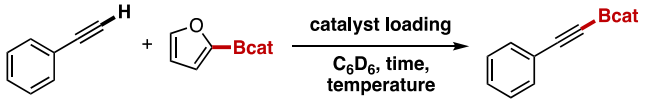


Scheme 4. Borylation scope for selected arenes. Conversion obtained via ^{1}H NMR by the consumption of the starting material in relationship with the internal standard. Reactions were carried out in a Teflon sealed NMR tube (J.-Young) with 0.15 mmol of substrate and a hexamethylbenzene internal standard.[a] Mixture of C2-, C3-borylated and C2,4-bisborylated products in a 0.09 mmol scale reaction with 5 equiv of 2a.

Borylation of terminal alkynes. While the reactivity with the *N*-($CH_2C{\equiv}CH$)-indole (**3b**) shows that the C-H activation at the 3-position of the indole is favored over the activation of the C-H bond of the alkyne (Scheme 4), we were curious to see if the latter type of activation was possible. Borylated alkynes are used in synthesis,[55] but the catalytic C-H borylation of alkynes is still underdeveloped compared to the activation of arenes. Ozerov and coworkers reported in 2013 an Ir catalyst for C-H borylation of these substrates.[56–58] By carefully designing a SiNN pincer ligand, they were able to steer the selectivity of their catalyst away from the usual aromatic Csp^2-H bonds towards Csp-H bonds. This discovery sparked the rapid development of new methodologies using various metals like Ag, Zn, Fe, Cu and Pd.[59–64] The first stoichiometric metal-free Csp-H bond activation using FLPs was reported by Stephan and collaborators in 2009[65] and the dehydroboration of terminal alkynes using borenium species was observed by Ingleson and collaborators in 2013,[73] but to our knowledge, no catalytic system has been developed for such a reaction.[43,49,65–74] The closest analogy has been reported by Repo, who demonstrated that alkynyl boranes could be generated in presence of BF_3 and bulky pentamethylpiperidine.[43]

Using 2-mercaptothiazole (**1a**) for the C-H borylation of phenylacetylene (**5a**) in the presence of 2-furylBcat (**2a**) gave only a 48 % conversion (Table 4, Entry 1). However, *N*-methyl-2-mercaptoimidazole (**1b**) reacted with phenylacetylene (**5a**) and 2-furylBcat to give 90 % of conversion after 18 h at 110 °C (Entry 3). While the reaction also worked with **1c** and **1d**, it provided low conversion of 66 % and 58 %, respectively (Entries 4 and 5). Increasing the catalyst loading, using excess of the boron source or increasing the reaction time did not give conversion over 90 % (Entries 6 to 8).

Table 4. Condition optimization for the borylation of phenylacetylene (5a).



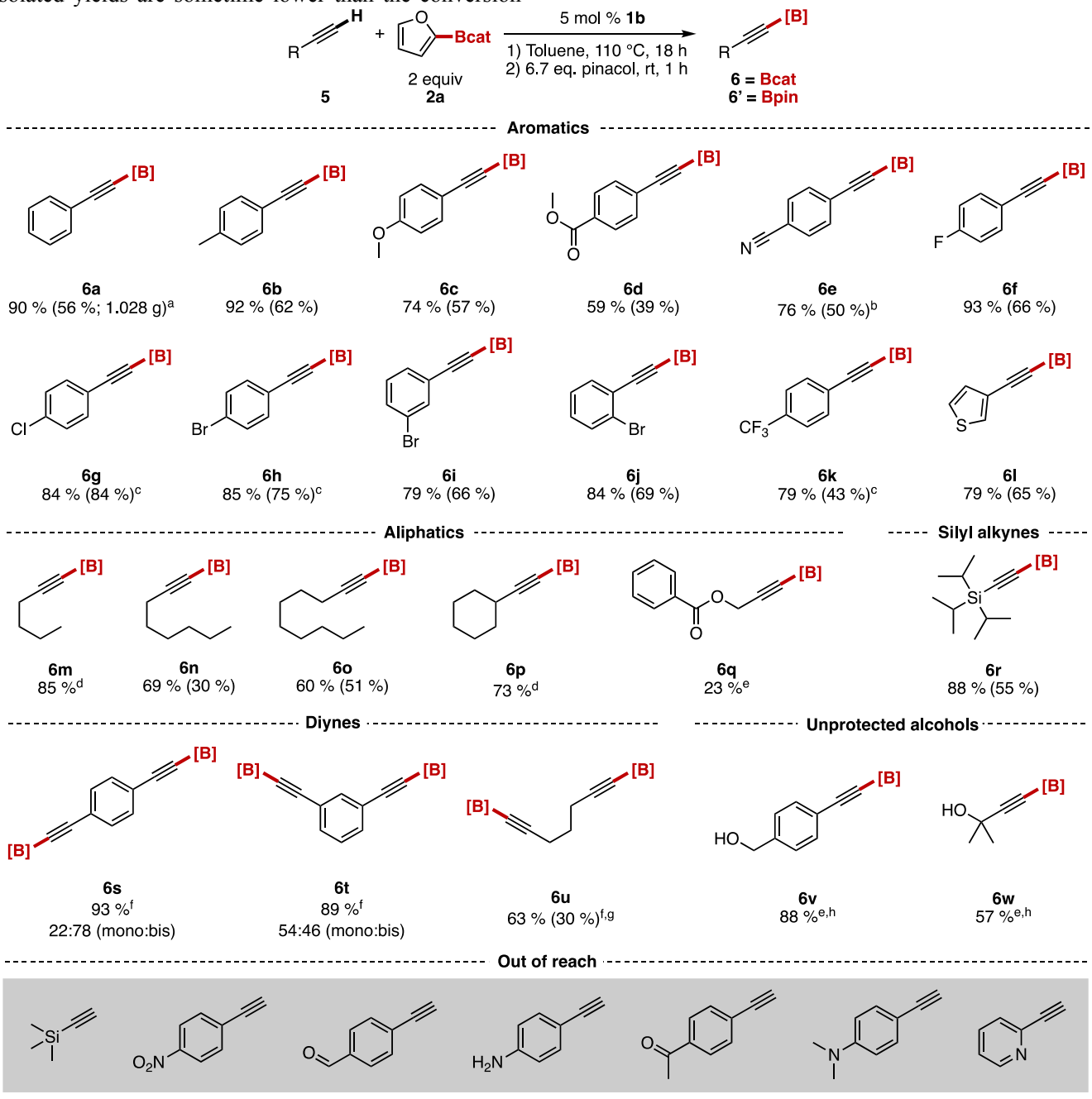
Entry	Catalyst	Temp	2a	Time	Conv.[a]
	(mol %)	°C	equiv	h	%
1	**1a** (5)	110	2	18	48
2	**1b** (5)	110	2	4	85
3	**1b (5)**	**110**	**2**	**18**	**90**
4	**1c** (5)	110	2	18	66
5	**1d** (25)	140	5	18	58
6	**1b** (5)	110	5	18	83
7	**1b** (10)	110	2	18	90
8	**1b** (5)	110	2	48	90

[a] Conversion obtained via ^{1}H NMR by the consumption of the starting material in relationship with the internal standard. Reactions were carried out in a Teflon sealed NMR tube (J.-Young) with 0.15 mmol of substrate and a hexamethylbenzene internal standard.

With these results in hand, we explored the scope of the reaction, as demonstrated in Scheme 5. Aromatic alkynes (**6a-l**) were smoothly borylated with good conversion. Under these catalytic conditions, the selectivity of the Csp-H over the Csp^2-H of arenes is excellent and with electron-rich 3-thienylacetylene (**6l**) no borylation on the thiophene ring was observed. However, since **3b** is selectively borylated at the C3 position, it should be noted that this selectivity remains substrate dependent. Aliphatic alkynes (**6m-p**) also underwent borylation with good conversions, although propargylic esters were more challenging (**6q**), obtaining only 23 % conversion. It is also possible to borylate the TIPS protected alkyne (**6r**), although the TMS analogue (**5x**) did not yield the desired product (*vide infra*). The borylation of diynes (**6s-u**) can also be achieved, giving a mixture of mono- and bis-borylated products in the presence 5 equiv of 2-furylBcat (**2a**). Interestingly, unprotected alcohols (**6v-w**) could also be borylated, but the reaction required 3 equiv of the boron source since 1 equivalent is consumed for the borylation of the O-H bond, which was shown to occur under 5 min at 20 °C.

This is particularly interesting since alcohols have been shown to inhibit the C-H borylation reaction with aminoborane catalysts.[30,75]

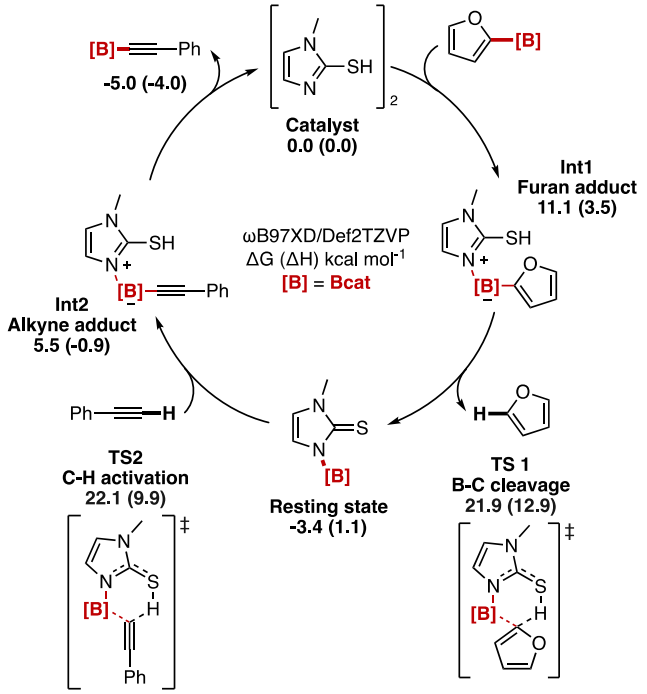
While the isolation of the alkynylBcat products was challenging, the transesterification to generate alkynylBpin followed by a short filtration on alumina and the removal of the remaining volatiles under vacuum yielded analytically pure samples. However, the isolated yields are sometime lower than the conversion since protodeborylation still occur during workup, especially with electron-deficient substrates. It is important to note that unlike previously reported methodologies,[76] the addition of triethylamine for the transesterification step lead to complete degradation of the product. These reactions can be carried out on the gram scale, as demonstrated with the isolation of 1.028 g of **6a**.



Scheme 5. Borylation scope for terminal alkynes. Conversion obtained via ^{1}H NMR by the consumption of the starting material in relationship with the internal standard. Isolated yields in parentheses. [a] 8.00 mmol scale reaction. See ESI. [b] Isolated as the catechol boronate ester. [c] Presence of impurities in the isolated product. [d] Too volatile for isolation. [e] Unstable product. [f] 0.09 mmol scale reaction with 5 equiv of 2a. [g] Bis borylated product isolated. [h] Reaction carried out using 3 equiv of 2a.

We investigated the mechanism of this transformation using DFT. We found the reaction operating according to a mechanism analogous to the arene transfer C-H borylation that we previously disclosed (Scheme 6).[33]

Both the transition states of the B-C bond cleavage (21.9 kcal mol^{-1}) and of the C-H activation (22.1 kcal mol^{-1}) are very close in energy. The overall process is exergonic by 5.0 kcal mol^{-1}, which is more important than the borylation of arenes since alkynylboronates are thermodynamically more stable than arylboronates.



Scheme 6. Mechanism of transfer C-H borylation of terminal alkynes.

To get a better understanding of this reaction, we also looked for deactivation pathways that could explain the low yields obtained with some substrates and catalysts. When reacting *p*-tolylacetylene (**5b**) with *N*-methyl-2-mercaptotimidazole (**1b**), no reaction occurred. However, adding 2-furylBcat (**2a**) to this reaction mixture led to the formation of a new product (**7b**), which is formally the addition product of the alkyne on the corresponding S/B Frustrated Lewis pair (Scheme 7), *i.e.* thioboration. ^{1}H NMR shows the disappearance of the Csp-H proton at δ 3.05 and the appearance of a new singlet at δ 6.51 corresponding to the olefinic proton formed during the thioboration. The ^{11}B NMR signal shifts from a broad singlet at δ 28.3 to a sharper singlet at δ 8.1, which is a chemical shift similar to previously reported intramolecular azole boronate adducts.[77]

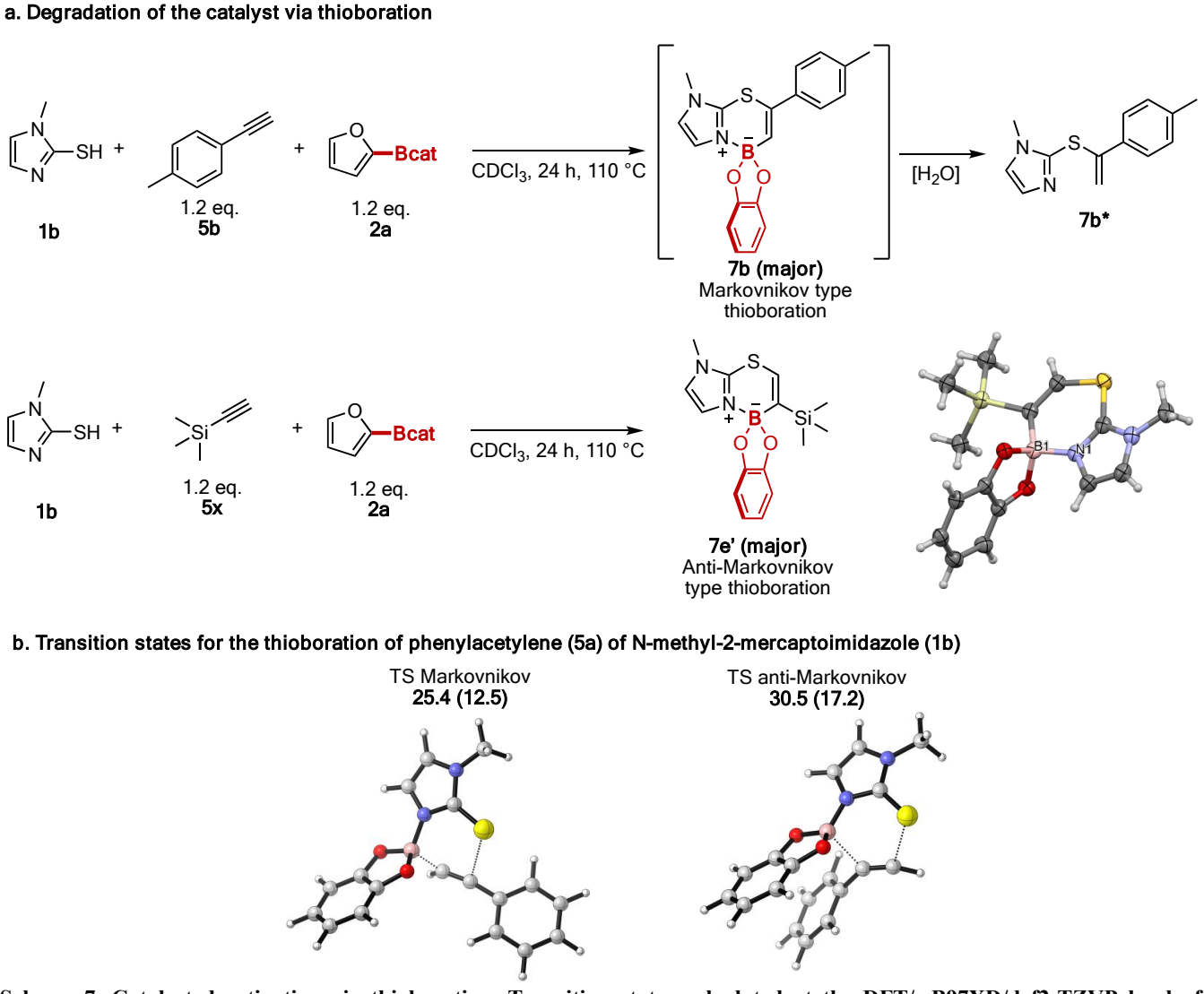
Similar reactivity was observed with every catalyst. These products were unstable. Instead, we were able to isolate the secondary alkenes **7a***, **7b*** and **7d*** (see Scheme 7a) resulting from the protodeborylation of the addition products, confirming the Markovnikov addition taking place. However, with TMS-acetylene, a substrate that was found particularly challenging to C-H borylate, we were able to isolate species **7e'**, which is formally the thioboration of the alkyne with catalyst **1b**. Its X-ray structural characterization supports our hypothesis (Scheme 7). The N1-B1 bond length of 1.573(2) Å is in the shorter range of dative N-B bonds,[78] supporting a strong interaction between the Lewis base and the boronate.

While several plausible mechanisms were tested using computational chemistry, the most viable pathway to obtain **7** is the concerted nucleophilic attack by the thione and electrophilic boronation of the alkyne from the resting state. Such process is reminiscent of FLP addition chemistry.[49,68,79–85] While both Markovnikov and anti-Markovnikov additions are accessible, the former is favored by approximatively 5.1 kcal mol^{-1} (**1b**), explaining the selectivity observed with our substrates. Other mechanisms, such as the S-H addition of the alkynylboranate via the carbophilic activation of the alkyne by 2-furylBcat (**2a**), analogous to the work of Blum and co-workers, were not viable processes according to DFT.[86–88]

Computational chemistry clearly shows that 2-mercaptothiazole is more prone than other catalysts to generate the addition product, as the difference between the borylation and thioboration energies is only 1.8 kcal mol^{-1} (Table 5). On the other hand, *N*-methyl-2-mercaptoimidazole (**1b**) is the most selective for the borylation, by 3.3 kcal mol^{-1}.

Table 5. Transition state energies for C-H borylation of terminal alkyne and thioboration of phenylacetylene (5a) by 1a-1d calculated at DFT/ωB97XD/def2-TZVP level of theory.

Cat.	$\Delta G^{\ddagger}_{borylation}$	$\Delta G^{\ddagger}_{thioboration}$	$\Delta\Delta G^{\ddagger}$
	kcal mol^{-1}		
1a	22.4	24.3	1.8
1b	22.1	25.4	3.3
1c	22.3	24.5	2.3
1d	25.6	28.2	2.6



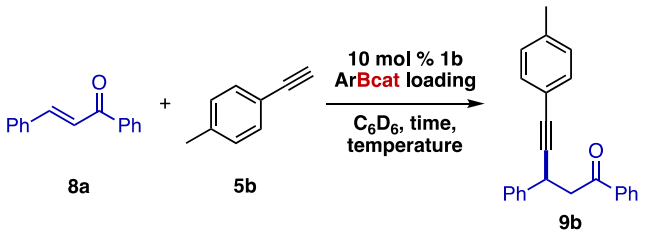
Scheme 7. Catalyst deactivation via thioboration. Transition states calculated at the DFT/ωB97XD/def2-TZVP level of theory, energies ΔG (ΔH) in kcal mol^{-1}. Thermal ellipsoid set at 50 % probability.

Catalytic 1,4 conjugate addition. We sought to develop a transformation where the boronate moiety could be recycled after the C-H borylation product was used as a reagent. We got inspired by the work of Chong and co-workers who reported that alkynyl boronates can undergo a metal-free conjugate 1,4-conjugate reaction with α-β unsaturated enones, such as chalconoids.[89] Although this reaction is usually assisted by transition metal catalysts,[90–92] we hypothesized that the catecholboronate would be electrophilic enough to make this reaction possible without the help of a transition metal. We also hypothesized that the enolization of the resulting product could act as a driving force for the catalyst to recover the boronate at the end of the reaction.

By using *trans*-chalcone (**8a**), we were able to carry out a one-pot borylation catalyzed by **1b**, followed by the 1,4-conjugate addition to yield addition product **9b** with 59 % conversion (see Table 6, Entry 1). Surprisingly, the addition product of 2-furylBcat (**2a**) was also observed, along with complete consumption of **8a**. To prevent this side-reaction, we used 4-anisylBcat **2b** as the boron source, which does not react with the chalcone by itself, allowing for 76 % conversion without any undesired side product (Table 6, Entry 2). Interestingly, we noted that only 37 % of **2b** was consumed during the reaction, hinting that the boronate moiety of the addition product could be reused as a borylation agent for the C-H borylation. It was demonstrated that a subs-stoichiometric amount of the boron source was required, since 55 % conversion (or 2.2 turnover) was observed when only 25 mol % of **2b** was used (Entry 3). Although **2c** and **2d** were initially considered unreactive boron sources, they also showed the ability to perform this reaction, albeit in lower yields (Entries 5 and 6). This suggests that the addition to the chalcone acts as a thermodynamic driving force for the transfer C-H borylation. Further optimization of the reaction conditions allowed to obtain quantitative conversions after 18 h at 110 °C using 10 mol % catalyst loading,

40 mol % of **2b** and 2 equiv of the alkyne (Entry 8). Therefore, it is possible to do the tandem C-H borylation/Michael addition of alkynes using *a sub-stoichiometric amount* of borylation agent.

Table 6. Condition optimization of the one-pot borylation and addition of terminal alkynes to α-β unsaturated ketones.



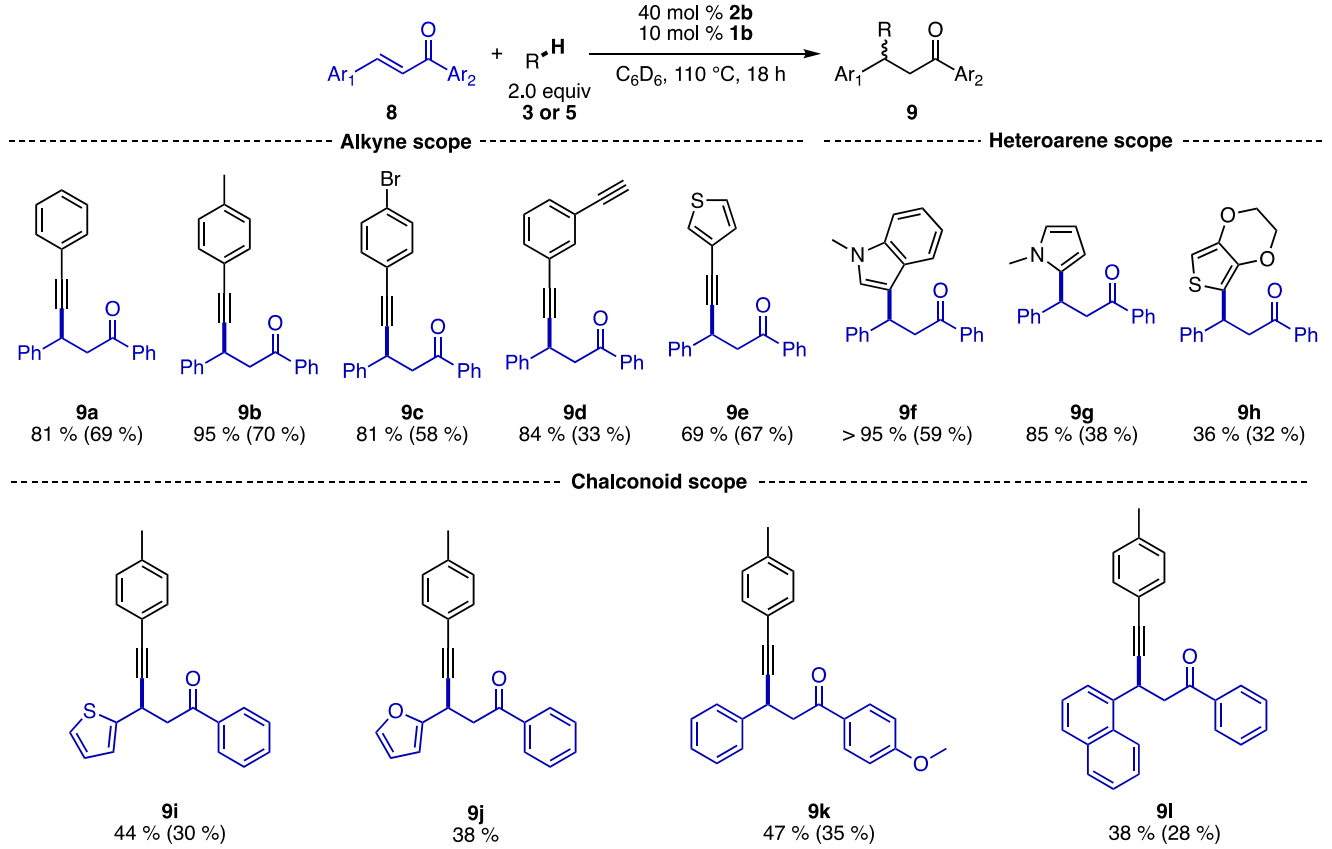
8a 5b 9b

Entry	5b	Ar-Bcat	Temp	Time	Conv.[a]
	equiv	(mol %)	°C	h	%
1	1.0	**2a** (200)	110	18	59[b]
2	1.0	**2b** (200)	110	18	75
3	1.0	**2b** (25)	110	18	50
4	1.0	**2b** (10)	110	18	22
5	1.0	**2c** (25)	110	18	32
6	1.0	**2d** (25)	110	18	16
7	2.0	**2b** (25)	110	18	64
8	2.0	**2b** (40)	110	18	> 95

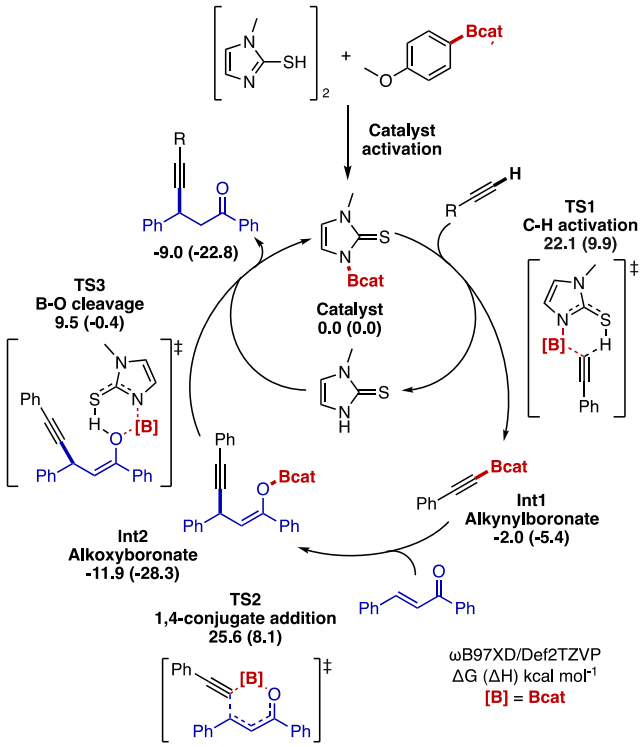
[a] Conversions obtained via ^{1}H NMR. Reactions were carried out in Teflon sealed NMR tube (J.-Young) with 0.15 mmol of substrate and a hexamethylbenzene internal standard. [b] Mixture of 9b and the addition product with 2a.

This reaction could operate using various arylacetylene derivatives with conversions up to 95% (Scheme 8, **9a-e**). Interestingly, it was possible to do the addition of heteroarenes such as indoles, pyrroles and thiophene to chalcone **8a** to generate products **9f-h**. Various chalconoids were also screened to give products **9i-l**. In several cases the yields are lower, which is mainly explained by the deactivation of the catalyst by thioboration of the alkyne, as previously discussed.

The mechanism was investigated by DFT (Scheme 9). As expected, the catalyst first cleaves the B-C bond of the borylation agent **2b** to generate the active B/S Lewis pair, which in turn can do the C-H activation of the alkyne with a barrier of 22.1 kcal mol^{-1}. The alkynyl boronate does the 1,4-conjugate addition with the chalcone to yield the alkoxyboronate intermediate. This step is rate limiting with an energy barrier of 25.6 kcal mol^{-1}. The boronate is then recovered by the catalyst with a low barrier of 9.5 kcal mol^{-1} for the B-O cleavage step. The enolization of the product makes this process exergonic by 9.0 kcal mol^{-1}. Although the inability to isolate alkynylBcat derivatives prevents the systematic spectroscopic monitoring of this transformation, we were able to observe each individual step in this transformation using furylBcat that is undergoing similar reactivity to alkynyl derivatives (see ESI pp S115-S120).



Scheme 8. Borylation/addition scope for terminal alkynes, arenes and chalconoids. Conversion obtained via ^{1}H NMR by the consumption of the starting material in relationship with the internal standard. Isolated yields in parentheses.



Scheme 9. Proposed catalytic cycle for the C-H borylation/1,4-conjugate addition.

CONCLUSION

In conclusion, we report a new generation of catalysts for the transfer C-H borylation of heteroarenes and alkynes. It was shown that the 2-mercapto-azole rings have a lower distortion energy in the transition state for the B-C bond cleavage, affording overall a more active system. While these catalysts are quite efficient, the thioboronate intermediates can undergo irreversible FLP-type addition with alkynes, leading to the deactivation of the catalyst. We also demonstrated that this catalytic system can do the tandem C-H borylation/1,4 conjugate addition of alkynes and heteroarenes using sub-stoichiometric amounts of boron precursors. We believe this boron recycling approach will find broader applications in all systems where arylboronates are used. We are notably looking at exploiting this concept in Miyaura-Suzuki coupling reactions, potentially removing the need for stoichiometric borylation reactions.

ASSOCIATED CONTENT

Supporting Information.
The Supporting Information is available free of charge on the ACS Publications website.

General procedures and characterization data (PDF)

Cartesian coordinates of all computed intermediates and transition states geometry (XYZ)
Crystallographic data of 7e' (CIF)

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