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Organobase-catalyzed 1,1-diborylation of terminal alkynes under metal-free conditions†

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An organobase-catalyzed 1,1-diborylation of terminal alkynes from propargylic derivatives with bis(2,4-dimethylpentane-2,4-glycolato)diboron (B_2oct_2) is first reported, regioselectively providing 1,1-diborylalkene products with high efficiency. The catalytic pathway is well postulated on the basis of DFT calculations.

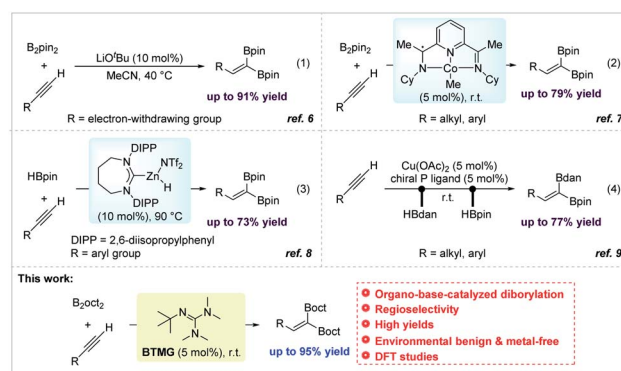
Organoboron compounds have attracted much attention as versatile building blocks in the synthesis of carbon–carbon and carbon heteroatom bonds,¹ which main features are their stability and ease of handling. Among this important class of reagents, 1,1-diborylalkenes are of particular interest, in part due to that the two geminal boron moieties can be differentiated and transformed *via* Pd-catalyzed cross-coupling reactions in a progressive manner to provide the bioactive and functional polysubstituted alkene motifs.^{2,3} Sequent manipulations of 1,1-diborylalkenes with different electrophiles allow for the stereoselective synthesis of challenging unsymmetrically substituted alkenes.⁴ What's noteworthy, is that the presence of the geminal boron moiety always has a positive effect on the first cross-coupling reaction. Owing to the significance of 1,1-diborylalkenes as general reaction intermediates in organic synthesis, developing efficient and practical methods for their synthesis is highly desirable.

In comparison with previous multi-step routes, 1,1-diborylation of terminal alkynes with diboron reagents represents one of the most step-economical and atom-economical strategies for synthesis of 1,1-diborylalkenes.⁵ In recent years, several elegant works were continuously discovered.^{6–9} Sawamura reported a seminal 1,1-diborylation of terminal propargylic derivatives with bis(pinacolato)diboron (B_2pin_2) catalyzed by a strong inorganic base (LiO^tBu) for the preparation of 1,1-diborylalkenes (Scheme 1, eqn (1)).⁶ A mild 1,1-diborylation of terminal alkynes with B_2pin_2 catalyzed by a cobalt complex was explored by Chirik and co-workers (Scheme 1, eqn (2)).⁷ What's more, stereoselective 1,1-diborylation products with two different boron substituents could be realized using an

unsymmetrical diboron reagent pinB–Bdan (dan = naphthalene-1,8-diaminato). After that, Ingleson successfully developed a low-coordinate NHC–zinc hydride complex-catalyzed 1,1-diborylation of terminal alkynes using pinacolborane (HBpin) *via* C–H borylation and hydroboration process (Scheme 1, eqn (3)).⁸ In 2020, Engle and co-workers explored a copper-catalyzed protocol for the stereodefined 1,1-diborylation of terminal alkynes, involving a sequential dehydrogenative borylation of the alkyne substrate with 1,8-diaminonaphthalatoborane (HBdan), followed by hydroboration with HBpin (Scheme 1, eqn (4)).⁹ Although having achieved such progress, relatively harsh reaction conditions, expensive ligand or preformed catalyst were always involved. Therefore, development of user-friendly and environmental benign protocols for preparation of 1,1-diborylalkenes is still highly desirable to meet the requirements of sustainable development in the field of scientific research and industrial production. In this context, we report on an environmental benign and metal-free protocol for 1,1-diborylation of terminal alkynes with bis(2,4-dimethylpentane-2,4-glycolato)diboron (B_2oct_2) under the catalysis of organobase 2-*tert*-Butyl-1,1,3,3-tetramethylguanidine (BTMG) at room temperature.

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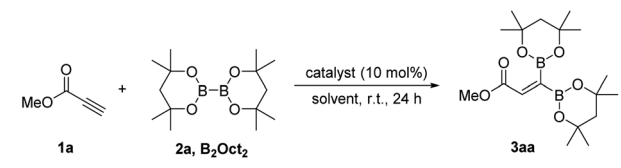
 † Electronic supplementary information (ESI) available. See <https://doi.org/10.1039/d2ra02638d>


Scheme 1 Previous work on 1,1-diborylation and our work.



Inspired by Sawamura's strong inorganic base catalyzed 1,1-diborylation strategy⁶ and the rapid development of organo-catalysis in recent years,¹⁰ we focused on the role of organic base as catalyst in this type of reaction. At the outset, a commercially strong organic base 1,1,3,3-tetramethylguanidine (TMG) was selected as the catalyst to verify its catalytic reactivity in the reaction between methyl propiolate **1a** and B₂oct₂ **2a**. The effect of solvent was initially evaluated and the results indicated that hexane, dichloromethane, 1,2-dichloroethane and toluene all failed to afford the desired *gem*-diborylated product (Table 1, entries 1–4). To our delight, when CCl₄ was used as the solvent, 17% yield of product **3aa** was obtained (entry 5). Whereas, further solvent screening experiments with THF, Et₂O, and EtOAc gave only inferior results (entries 6–8). A slightly higher yield of 35% was obtained utilizing DMF as the solvent (entry 9). Gratifyingly, the yield of **3aa** was dramatically increased to 79%

Table 1 Condition optimization^a



Entry	Solvent	Catalyst (mol%)	Yield ^b (%)
1	Hexane	TMG	0
2	DCM	TMG	0
3	DCE	TMG	0
4	Toluene	TMG	0
5	CCl ₄	TMG	17
6	THF	TMG	7
7	Et ₂ O	TMG	5
8	EtOAc	TMG	4
9	DMF	TMG	35
10	MeCN	TMG	79
11	MeCN	Et ₃ N	95
12	MeCN	BTMG	98 (95) ^c
13	MeCN	TMEDA	77
14	MeCN	TBD	0
15	MeCN	DBU	0
16	MeCN	Pyridine	0
17	MeCN	Quinine	0
18	MeCN	DMAP	12
19	MeCN	2,6-Lutidine	19
20	MeCN	Li ₂ CO ₃	0
21	MeCN	Na ₂ CO ₃	0
22	MeCN	K ₂ CO ₃	0
23	MeCN	Cs ₂ CO ₃	95
24	MeCN	NaOH	95
25	MeCN	LiO ^t Bu	0
26	MeCN	—	0
27 ^d	MeCN	BTMG	96 (94) ^c
28 ^d	MeCN	Et ₃ N	65
29 ^d	MeCN	Cs ₂ CO ₃	21
30 ^d	MeCN	NaOH	86

^a Reaction conditions: methyl propiolate **1a** (0.1 mmol), B₂oct₂ **2a** (0.1 mmol), catalyst (10 mol%), solvent (2 mL), rt., 24 h. ^b Yields determined by GC-MS. ^c Isolated yields in parenthesis. ^d 5 mol% of catalyst was employed.

when MeCN was employed as the solvent (entry 10). Then, organobase catalyst screening was performed (entries 11–19), among which organobase like Et₃N, BTMG and TMEDA all proved being effective catalysts, producing **3aa** in yields of 95%, 98% and 77%, respectively (entries 11–13). However, other organobases like TBD, DBU, pyridine and quinine all showed nearly no catalytic activity (entries 14–17). DMAP and 2,6-lutidine were not the proper catalyst because the yields were less than 20% (entries 18–19). Several kinds of inorganic base were also tested to catalyze our reaction, carbonates (K₂CO₃, Na₂CO₃, and Li₂CO₃) all led to the failure of the reaction (entries 20–22), nevertheless, Cs₂CO₃ and NaOH showed excellent performance with formation of product **3aa** in 95% yield (entries 23–24). The strong inorganic base (LiO^tBu), which was employed in Sawamura's work,⁶ exhibited no catalytic activity (entry 25) and the high catalytic activity of Et₃N and Cs₂CO₃ indicated that the alkalinity of the base may be not the critical factor for this reaction (entries 11 and 23). When the transformation was conducted in the absence of catalyst, no product was observed (entry 26). It is noteworthy that further lowering the loading of BTMG to 5 mol%, a still high yield of 96% was obtained (entry 27). However, when the loading of other bases (Et₃N, Cs₂CO₃ and NaOH) was also lowered to 5 mol%, an obvious reduction of yields was observed (entries 28–30). Therefore, the catalytic system consisting of 5 mol% BTMG as the catalyst in MeCN performed well as the optimal conditions.

With optimized conditions in hand, we next sought to investigate the scope of this regioselective 1,1-diborylation with respect to the alkyne component (Table 2). A broad array of propargylic derivatives can effectively serve as coupling partners. Linear alkyl ester group of propargyl acid such as methyl, ethyl, *n*-propyl, *n*-butyl and *n*-pentyl were well-tolerated to furnish 1,1-diborylated products in excellent yield (entries 1–5, 88–94% yield). Steric bulk proximal to the ester functionality is compatible, as exemplified by the presence of isopropyl, isobutyl, *tert*-butyl and isopentyl substituents (entries 6–9, 86–91 yield%). We found that benzyl and 1-phenylpropyl propiolate also participated readily to give the corresponding products in a yield of 92% and 78%, respectively (entries 10–11). Moreover, 4-chlorophenethyl propiolate was found to be a competent substrate with the chloro-group remaining unreacted in this transformation (entry 12, 93% yield). Phenyl propionate reacted well to form the desired diborylated product **3ma** in 78% yield (entry 13). Notably, *N*-methyl-*N*-phenylpropionamide also showed good reactivity towards such diborylation reaction, which provided the desired product **3na** in 53% yield (entry 14).

The diborylation of propiolate esters bearing a terminal alkenyl group all proceeded well to give the diborylated products and kept the alkenyl group untouched (entries 15–17, 89–93% yield). It should be mentioned that diyne substrates demonstrate exceptional chemoselectivity and undergoes 1,1-diborylation exclusively at the site of propionic acid (entries 18–19, 82–88% yield). Unfortunately, attempts to run the diborylation reaction with other types of alkynes resulted in frustrating results (for more details, please see ESI†).

We also examined the *gem*-diborylation reaction of methyl propiolate **1a** with other types of diboron reagents (Scheme 2).

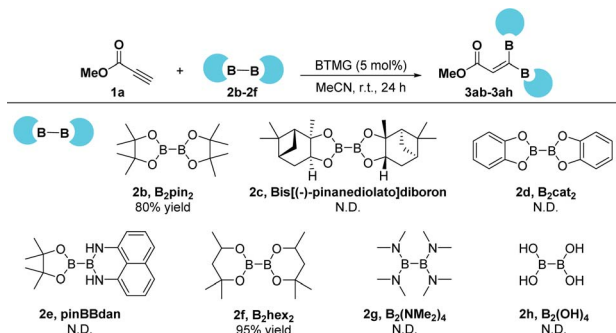


Table 2 Substrate scope for 1,1-diborylation^{a,b}

Entry	Alkyne	Product	Yield (%)
1			94
2			93
3			93
4			89
5			88
6			91
7			87
8			86
9			90
10			92
11			78
12			93
13			73
14			53
15			89
16			93
17			93
18			82
19			88

^a Reaction conditions: alkyne (0.1 mmol), B₂oct₂ (0.1 mmol), BTMG (5 mol%), MeCN (2 mL), rt., 24 h. ^b Isolated yield.

The 1,1-diborylation reaction proceeded well when B₂pin₂ (**2b**) was used as the diborylating reagent, affording the title diborylated product **3ab** in 80% isolated yield. It should be



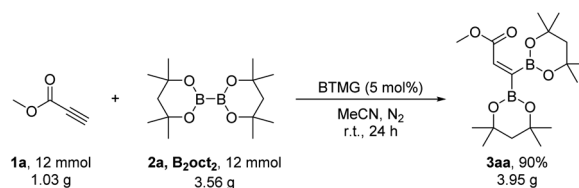
Scheme 2 1,1-Diborylation reaction using other diboron reagents. Reaction conditions: methyl propiolate (0.1 mmol), diboron reagent (0.1 mmol), BTMG (5 mol%), MeCN (2 mL), rt., 24 h. N.D. = not detected.

noted that a comparable yield of 95% was achieved when another six-membered partner B₂hex₂ (**2f**) was employed. However, other diboron compounds, such as Bis[(-)-pinanediolato]diboron (**2c**), B₂cat₂ (**2d**), pinBBdan (**2e**), B₂(NMe₂)₄ (**2g**), and B₂(OH)₂ (**2h**) proved to be ineffective under this 1,1-diborylation reaction.

To demonstrate the practicability and scalability of our methodology, the gram-scale 1,1-diborylation of methyl propiolate **1a** with B₂oct₂ (**2a**) was carried out on 12 mmol to produce **3aa** in 90% yield (3.95 g) (Scheme 3).

To better understand the reaction pathway for organobase-catalyzed 1,1-diborylation of terminal alkynes, DFT studies are performed using methyl propiolate **1a** and B₂oct₂ (**2a**) as the model substrate and BTMG as the organobase. The calculated energy profile is shown in Fig. 1. The initial step is a concerted three-component proton transfer/borylation process (**TS1**), the base (BTMG) helps to abstract a proton from the terminal alkyne **1a** to give alkynyl anion **I** and protonated base. At the same time, the negatively charged terminal carbon of the alkyne could attack the boron center of the diboron species, leading to a two-component intermediate **II**. Then the negatively charged diboron species would undergo a 1,2-boryl migration process (**TS2**) to generate a 1,1-diboryllallene species **III**. Finally, another proton transfer (**TS3**) from protonated base generated in the previous step to the negative-charged oxygen atom of the allene species **II** to give an allene hemiacetal **IV**, which then tautomerizes to the 1,1-diborylated product **3aa**.

Based on the results of previous work⁶ and our DFT studies, a plausible reaction pathway was postulated as in Scheme 4. Methyl propiolate **1a** is firstly deprotonated in the presence of an organobase to give an alkynyl anion **I**, which then



Scheme 3 Scale up synthesis.



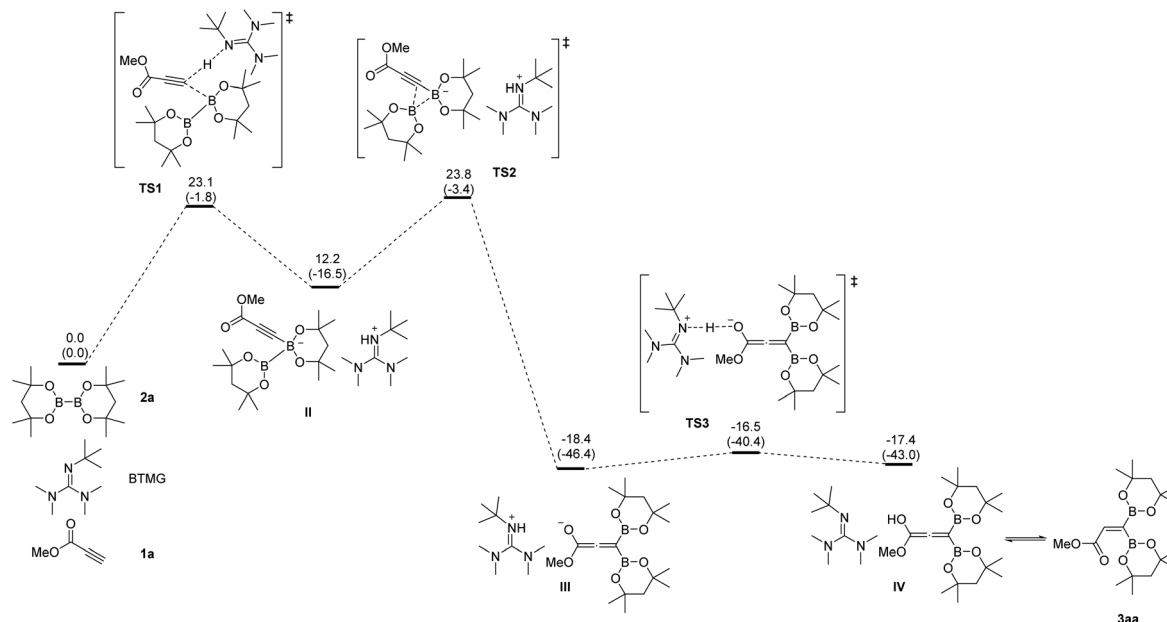
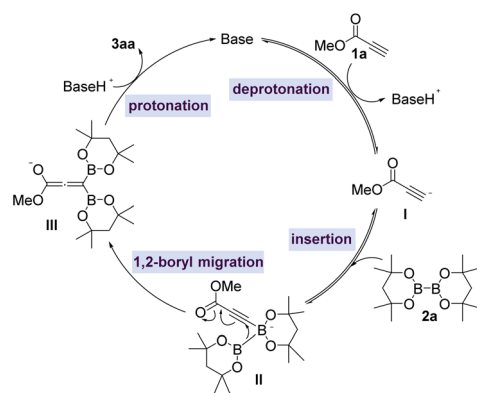


Fig. 1 Energy profile calculated for the organobase-catalyzed 1,1-diborylation of methyl propiolate. Relative free energies and electronic energies (in parentheses) are given in kcal mol⁻¹.



Scheme 4 Proposed catalytic mechanism.

nucleophilically attacks the diboron reagent **2a** to form an alkyne diboron complex **II**. Complex **II** occurs a 1,2-boryl migration process to produce a *gem*-diboryllene intermediate **III**, followed by a protonation to afford the 1,1-diborylalkene product **3aa** with releasing the organobase catalyst to complete the catalytic cycle.

Conclusions

In conclusion, an efficient and practical methodology for 1,1-diborylation of terminal alkynes were well developed by the catalysis of a commercially available organobase under mild conditions. Employing B₂Oct₂ as the diborylating reagent, a series of propargylic derivatives was confirmed to be of high efficiency towards this regioselective 1,1-diborylation reaction. DFT calculations were introduced to well demonstrate the catalytic mechanism. This work provides an alternative

approach for the preparation of synthetically important 1,1-diborylalkenes.

Conflicts of interest

There are no conflicts to declare.

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