Complex Boron-Containing Molecules through a 1,2-Metalate Rearrangement/anti-\(S_N2'\) Elimination/Cycloaddition Reaction Sequence

Chloe Tillin  
Raphael Bigler  
Renata Calo-Lapido  
Beatrice S. L. Collins  
Adam Noble  
Varinder K. Aggarwal*  

School of Chemistry, University of Bristol, Cantock’s Close, Bristol BS8 1TS, UK  
v.aggarwal@bristol.ac.uk

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Abstract  
The three-component coupling of benzylamines, boronic esters, and \(\text{4-phenyl-3H-1,2,4-triazole-3,5(4H)-dione}\) (PTAD) is reported. The boronate complex formed from an ortho-lithiated benzyamine and a boronic ester undergoes a stereospecific 1,2-metalate rearrangement/anti-\(S_N2'\) elimination in the presence of an N-activator to provide a deaeromatized tertiary boronic ester. Interception of this deaeromatized intermediate with a dienophile leads to stereopredictable cycloaddition reactions to generate highly complex three-dimensional boron-containing molecular structures. When enantioenriched \(\alpha\)-methyl-substituted benzylamines are employed, the corresponding cycloaddition adducts are formed with excellent enantiospecificities.

Key words  
cy cloaddition, 1,2-metalate rearrangement, phenyltriazoleidine, benzylamines, boronic esters, multicomponent reaction

Boronic esters are highly versatile molecules in organic synthesis due to the wealth of stereospecific transformations that they have been shown to undergo. Transformation into alcohols, amines, halogens, or unsaturated carbon moieties (alkenes or alkynes) can occur through stereoregulative or stereoinvertive pathways, whereas homologation reactions can be used to build up complex carbon skeletons.\(^1,2\) Furthermore, \(\alpha\)-amino boronic acids have been shown to act as potent inhibitors of serine protease, leading to the development of, for example, bortezomib, a treatment for relapsed and refractory multiple myeloma.\(^3\) Thus, the development of novel methods for the synthesis of alkyl boronic esters with high enantiopurity is of utmost importance. Although recent years have seen a huge growth in the development of such methods,\(^4\) access to structurally complex alkyl boronic esters possessing an array of useful functionalities remains a challenge. We were interested in the development of a method for the synthesis of densely functionalized organoboron molecules, rich in orthogonal functionality that could be used for subsequent synthetic elaboration. Here, we detail a simple one-pot procedure that generates complex three-dimensional boron-containing architectures that bear multiple sites of orthogonal reactivity.

We recently reported a method for the enantiospecific synthesis of ortho-substituted benzylboronic esters by a 1,2-metalate rearrangement/anti-\(S_N2'\) elimination/1,3-borotropic shift reaction sequence starting from enantioenriched \(\alpha\)-substituted benzylamines [Scheme 1(A)].\(^3\) This reaction sequence passes through a key deaeromatized tertiary boronic ester intermediate \(\text{Int-I}\), with the subsequent 1,3-borotropic shift driven by the favorable rearomatization. We have also shown that this key enantioenriched deaeromatized intermediate can participate in allylboration and allylic Suzuki–Miyaura cross-coupling reactions to provide complex enantioenriched products [Scheme 1(B)].\(^5,6\) Importantly, all of these transformations use rearomatization as a driving forcing. We were, however, interested in diverting reactivity along an alternative pathway, avoiding rearomatization and thereby retaining valuable functionality. In this way, we postulated that we might be able to intercept the deaeromatized intermediate \(\text{Int-I}\) through a Diels–Alder cycloaddition reaction with an appropriate dienophile. As depicted in Scheme 1(C), this should give rise to complex three-dimensional architectures that possess not only a tertiary boronic ester moiety, but also two electronically differentiated alkene moieties (an allyl boronic ester and an isolated alkene), along with the functionalities associated with the boronic ester component and the dienophile. Interception of deaeromatized intermediates has a significant history in organic synthesis, and it has been used in total syntheses\(^7\) and, more recently, as a powerful method in transition metal-catalyzed transformations.\(^8\) A number of issues were expected to arise in the realization of this pro-
cess, including (i) the well-known limited reactivity of cyclohexadienes, further compounded by the presence of a sterically demanding tertiary boronic ester; (ii) the facial selectivity in the Diels–Alder cycloaddition, which should give rise to diastereomeric mixtures; and (iii) the potential for matched/mismatched reactivities when both chiral benzylamines and boronic esters are used.

We began our studies by preparing the key dearomatized intermediate through treatment of lithiated benzylamine Li-1a with 2-cyclohexyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (CyBpin; 2a), followed by activation of the amine moiety with ClCO₂CMe₂CCl₃ (Me₂Troc–Cl), in line with our previous reports (Scheme 2). To our delight, the addition of 4-phenyl-3H-1,2,4-triazole-3,5(4H)-dione (PTAD; 1.1 equivalents) to the reaction mixture at room temperature, followed by stirring for one hour, provided cycloaddition product 3aa in 51% isolated yield and a remarkable dr of 17:1 (determined by ¹H NMR analysis of both the crude and purified product); the product was obtained as the syn-isomer (here, syn designates the relationship between the Bpin moiety and the triazolidine group). We chose PTAD as the dienophile on the basis of reports in the literature that addressed the poor reactivity of cyclohexadienes towards cycloaddition reactions due to the high distortion energies associated with accessing the transition-state geometry.⁹ Studies by Houk and co-workers investigated the superior reactivity of PTAD as a dienophile for such systems.¹⁰ Indeed, other dienophiles tested (e.g., maleic anhydride, diethyl acetylenedicarboxylate, and diethyl fumarate) were all unreactive.¹¹

We then went on to assess the scope of the boronic ester component by using the lithiated benzylamine Li-1a (Scheme 3). The Boc-protected piperidine boronic ester 2b provided the cycloaddition product 3ab in 67% yield and an excellent dr (>20:1), as did the 1-adamantyl boronic ester 2c (3ac; 42% yield, >20:1 dr). Interestingly, when the phenylboronic ester 2d was used, the syn-isomer was still favored, but diastereoselectivity was poor (1.5:1). Furthermore, where less sterically bulky boronic esters, such as the cyclopropyl boronic ester 2e or the primary boronic esters 2f–j were used, the diastereoselectivity was inverted to favor the anti-isomer. The entries shown in Scheme 3 also highlight the range of functionalities tolerated by the reaction, including protected alcohols (3ah) or aldehydes (3aj), along with azides (3ai) or carbamates (3ab).

We rationalize the selectivities observed in Scheme 3 as follows [Scheme 4(A)]. When the R group on the boronic ester is large (e.g., 3aa–ac in Scheme 3), the dienophile approaches the diene of Int-I past the smaller Bpin moiety, leading to the syn-isomer with high diastereoselectivity.
The remarkable diastereoselectivities observed in these cases indicate that the Bpin group, which is widely regarded as bulky, is considerably less sterically demanding than simple α-branched alkyl groups.\(^{12}\) When R is small, for example a cyclopropyl or primary alkyl group, the dienophile approaches past this group, avoiding the Bpin moiety, thereby providing the anti-isomer. In these cases, the steric difference between the smaller R group and the relatively small Bpin moiety is less, and the diastereoselectivity is correspondingly reduced. For the phenylboronic ester 2d, approach past the Bpin moiety is still favored, but with much lower selectivity.
The cycloaddition products were usually isolated as mixtures of diastereoisomers, and their relative configurations were assigned through analysis of the $^{13}$C NMR chemical shifts. For the anti-isomers, diagnostic downfield shifts are observed for one of the alkene signals, due to donation of electron density from the alkene into the proximal empty p-orbital on boron. These $^{13}$C NMR assignments were further supported by the separation of the syn- and anti-isomers for the cyclopropyl product 3ae; single-crystal X-ray diffraction analyses of the two isomers confirmed our assignments [Scheme 4(B)].

We then assessed the scope of the benzylamine component (Scheme 5). Methyl substituents were accommodated in both the meta- and ortho-positions (3ba and 3ca), and fluorine substituents were also tolerated (3da and 3ea). Interestingly, whereas putative cycloaddition adducts could be identified in the crude $^1$H NMR spectra for electron-rich benzylamines, such as those bearing methoxy substituents, attempts to isolate these products by chromatography were frustrating, as despite extensive assessment of the chromatographic medium, no product could be isolated. We postulate that the enol ether present in such cycloadducts might be activated by the silica during chromatography, facilitating a series of deleterious side reactions.

We then addressed enantioenriched $\alpha$-methyl-substituted benzylamines. We have previously reported that the 1,2-metallate rearrangement/anti-$S_N$2$'$ elimination sequence proceeds with excellent enantiospecificity for secondary boronic esters due to a selective N-acylation of a low-energy conformation of the boronate complex, in which the hydrogen atom of the benzylic position lies in the plane of the aromatic ring towards the boronate.$^5$ This leads to the generation of the tertiary boronic ester dearomatized intermediate Int-1 in excellent levels of enantiospecificity. We expected this enantioenrichment to be transferred directly through the cycloaddition process, and this was borne out by the generation of cycloadduct 3fa from the $\alpha$-methyl-substituted benzylamine 1f (97:3 er) in 69% yield, 95:5 er, and >20:1 dr (Scheme 6). Primary alkyl boronic ester 2g provided cycloadduct 3fg in 30% yield, 91:9 er, and 1:2.2 dr in favor of the anti-isomer (the er refers to the major anti-diastereoisomer, but this is expected to be the same for the minor syn-diastereoisomer). When we used both enantioenriched chiral amine 1f and enantioenriched boronic ester 2k (95:5 er), cycloadduct 3fk was formed in 9:1 dr with respect to all other isomers. The use of the opposite enantiomer of the benzylamine 1g (1:99 er) provided cycloadduct 3gk in similar yield and diastereoselectivity, indicating no matched/mismatched behavior. Such behavior was also observed when the menthol-derived boronic ester 2i reacted with the two enantiomers of the $\alpha$-methyl-substituted benzylamine to provide 3fi (17:1 dr) and 3gli (>20:1 dr).

In summary, we have developed an enantiospecific, one-pot, 1,2-metallate rearrangement/anti-$S_N$2$'$ elimination/cycloaddition reaction sequence that generates complex three-dimensional structures with exquisite enantioselectivity and predictable diastereoselectivities. The convergent three-component nature of this process leads to structures bearing diverse orthogonal functionalities. Studies are ongoing to exploit this functionality in subsequent transformations, so as to permit access to valuable, densely functionalized, chiral building blocks.

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**Supporting Information**

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Boronic ester 2a (500 μmol) was added to the ortho-lithiated benzylamine Li-1a (525 μmol, 1.05 equiv; prepared from 1a) in THF (2 mL) at –78 °C, and the solution was stirred at –78 °C for 15 min, after which the cooling bath was removed, and the mixture was stirred for a further 15 min. CICO₂CMe₂C≡C (132.0 mg, 550 μmol, 1.10 equiv) was added at –78 °C, and the solution was stirred for 15 min at –78 °C, after which the cooling bath was removed and the mixture was stirred for a further 5 min. PTAD (96.3 mg, 550 μmol, 1.10 equiv) was added, and the solution was stirred for 1 h at r.t. CH₃Cl (50 mL) was added and the solution was washed with H₂O (25 mL) and sat. aq NaCl (25 mL), then dried (MgSO₄), filtered, and concentrated under reduced pressure. Purification by flash column chromatography (silica gel, EtOAc–pentane (15:85)) gave a white solid; yield: 121 mg (50%), dr = 17:1; mp 86 °C, 1.10 equiv) was added, and the solution was stirred for 1 h at r.t. 1H NMR (400 MHz, CDCl₃): δ = 7.48–7.36 (m, 4 H, Ar-H), 7.34–7.28 (m, 1 H, Ar-H), 6.50 (ddd, 3 JHH = 7.48, 7.36, 4.0 Hz, 4 H), 5.26–5.21 [m, 2 H, =C=JH=1.7 Hz, 1 H, C=JH=7.48, 7.36, 4.0 Hz, 4 H], 5.11 (dd, 3 JHH = 5.5 Hz, 3 JHF = 1.8 Hz, 1 H, =CH), 4.63 (ddd, 3 JHH = 7.48, 7.36, 4.0 Hz, 4 H), 3.59 (s, 1 H, =CHN), 2.56–2.51 [m, 2 H, =CHN (1 H) + CHN (1 H)], 2.29 [2, 1H, =CHN], 2.19 [2, 1H, =CHN], 2.08–2.00 (m, 1 H, CHN), 1.79–1.61 (m, 4 H, CH₂), 1.26 [s, 6 H, CH₃ (pin)], 1.24 [s, 6 H, CH₃ (pin)]. 11B{1H} NMR (128 MHz, CDCl₃): δ = 135.8 (CD), 155.3 (CO), 142.9 (σc), 131.8 (arom.), 129.9 (=CH), 129.0 (2 C, arom.), 128.6 (=CH), 128.0 (arom.), 113.9 (=C=), 103.6 (C=), 31.0 (CD), 29.8 (CH₂), 27.3 (CH), 27.1 (CH), 26.4 (CH₂), 25.1 [2 C, CH₃ (pin)], 24.4 [2 C, CH₃ (pin)]. Carbons attached to boron were not observed due to quadrupolar relaxation. 11B{1H} NMR (128 MHz, CDCl₃): δ 33.5 (br s). HRMS (ESI): m/z [M + Na⁺] calcld for C₂₂H₁₄BN₂NaO₄: 498.2553; found: 498.2554.