Synthesis of the C18-C27 Fragment of Georatusin

Yannick Linne, Maike Birkner, and Markus Kalesse

Institute of Organic Chemistry Gottfried Wilhelm Leibniz Universität Hannover, 30167 Hannover (Germany)
Email: markus.kalesse@oci.uni-hannover.de yannick.linne@oci.uni-hannover.de

Dedicated to Professor Dr. Horst Kunz on the occasion of his 80th birthday

Received 08-21-2020 Accepted 10-21-2020 Published on line 11-08-2020

Abstract

Anti-configured 1,3-dimethyl deoxypropionate motifs are important sub-structures in natural products. We describe a bidirectional approach for the rapid construction of highly reduced polyketide fragments for the synthesis of georatusin employing our mono-Zweifel protocol.

Keywords: Georatusin, desymmetrization, C2-symmetry, mono-Zweifel olefination
Introduction

In the context of our program to establish synthetic access to various natural products\textsuperscript{1-16} we focused on those featuring the 1,3-(poly)deoxypropionate motif. A structurally challenging example is the polyketide-peptide hybrid georatusin (1) which was isolated from the soil fungus \textit{Geomyces auratus} in 2018 by Bode and coworkers.\textsuperscript{17} Georatusin (1) features a highly reduced and methylated polyketide fragment (blue) fused to a \textit{D}-tryptophan moiety (red) forming a 13-membered ring (Figure 1).\textsuperscript{17}

![Figure 1. Structure of the highly reduced polyketide-peptide hybrid georatusin (1).](image)

This 13-membered ring contains nine of the overall eleven stereogenic centers. The Bode group was able to determine the absolute configuration of the tryptophan unit via comparison of the ECD spectra of \textit{L}- and \textit{D}-tryptophan whereas the other stereogenic centers were determined in a relative fashion using different NMR experiments but could not be set into relation with the \textit{D}-tryptophan moiety.\textsuperscript{17} Due to its highly reduced carbon skeleton georatusin (1) is challenging to synthesize without several functional group interconversions using classic aldol chemistry. We planned to synthesize most of the carbon skeleton via lithiation-borylation chemistry using \textit{C}_2-symmetric 1,3-bis(boronic ester) 3 and its derived fragments 4 and 5 (Scheme 1). The strategic advantage of this strategy is the fact, compound 5 can be directly obtained through hydrogenation from 4 and the \textit{C}_2-symmetric compound 3 on the other hand allows rapid access to 4. Due to the \textit{C}_2-symmetry no side differentiation of 3 is required prior to the Zweifel olefination.

![Scheme 1. First generation retrosynthetic analysis of georatusin (1).](image)
Results and Discussion

Our synthesis started with the gram-scale preparation of known C₂-symmetric 1,3-bis(boronic ester) 3¹⁸,¹⁹ employing our protocol.¹⁹ Starting from our key building block 3 the precursor of the other two fragments is readily available using a three step sequence consisting of our mono-Zweifel olefination protocol,¹⁹ Matteson-homologation²⁰ and oxidation (Scheme 2).

Scheme 2. Synthesis of C₂-symmetric 1,3-bis(boronic ester) 3 and the precursor of the remaining fragments.

Alcohol 8 was then converted into carbamate 9 using established conditions.²¹,²² Fragment coupling of the resulting carbamate 9 with C₂-symmetric 1,3-bis(boronic ester) 3 via the lithiation-borylation protocol gave the desired mono-product 10 in 17% yield (Scheme 3).

Scheme 3. Synthesis of carbamate 9 and first generation fragment coupling.

Based on deprotonation experiments of carbamate 9 we observed that the H-D exchange was only 35% using the standard lithiation conditions. The best result was obtained with a lithiation time of 16 h and slightly increased equivalents of (+)-sparteine and sBuLi (Table 1). The use of different bases did not lead to lithiation or in the case of iPrLi only to moderate yields. Therefore, we switched to the corresponding TIB ester 11²¹,²² which could be completely lithiated under the standard conditions.
Table 1. Lithiation experiments

| Entry | Substrate | Base | Lithiation time, h | H-D-Exchange, %d |
|-------|-----------|------|-------------------|------------------|
| 1a    | carbamate 9 | sBuLi | 5                 | 35               |
| 2a    | carbamate 9 | sBuLi | 13                | 35               |
| 3b    | carbamate 9 | sBuLi | 5                 | 19               |
| 4c    | carbamate 9 | sBuLi | 16                | 56               |
| 5a    | carbamate 9 | tBuLi | 5                 | 0                |
| 6c    | carbamate 9 | nBuLi | 22                | 0                |
| 7c    | carbamate 9 | MeLi  | 8                 | 0                |
| 8c    | carbamate 9 | iPrLi | 17                | 42               |
| 9c    | TIB ester 11 | sBuLi | 5                 | 100              |

*aLithiation conditions: substrate (1.0 equiv.), (+)-sparteine (1.3 equiv.), base (1.3 equiv.), Et₂O, −78 °C, lithiation time, then D₂O (excess) at −78 °C to rt, 0.5 h. bBase (1.8 equiv.). c(+)-Sparteine (1.6 equiv.), base (1.5 equiv.). d Determined by 1H-NMR.

With an effective lithiation strategy in hand, we again performed the fragment coupling and obtained the desired 1,4-bis(boronic ester) 10 in 41% yield. Since the desired product was hard to separate from the double homologation product, we started to optimize the borylation step (Table 2). The addition of additives like Et₃N and PPh₃ which should form an ate-complex with one of the boronic esters did not improve the yield. Short time for ate-complex formation (1 h) increases the mono:di ratio in a significant way but an even shorter ate-complex formation (<1 h) resulted in a remarkable drop of the yield.

Table 2. Optimization of first generation fragment coupling

| Entry | Additive | Time ate-complex, h | Yield, %b | Mono : di ratio c |
|-------|----------|---------------------|------------|------------------|
| 1a    | -        | 2.5                 | 22         | 1.5:1            |
| 2a    | Et₃N    | 1.5                 | 20         | 1.7:1            |
| 3a    | PPh₃    | 1.5                 | 19         | 1.6:1            |
| 4a    | -        | 1                   | 41         | 4.1:1            |
| 5a    | -        | 0.5                 | 20         | 2.5:1            |
Table 2. Continued

a: DIAD, TIBOH, PPh₃, THF, 0 °C to rt, o/n, 94%. a reaction conditions: 11 (1.0 equiv.), (+)-sparteine (1.6 equiv.), sBuLi (1.5 equiv.), additive (1.5 equiv.), Et₂O, 0°78 °C, 5 h, then 3, Et₂O, 0°78 °C to rt, o/n. b Isolated yield after flash column chromatography. c Based on the isolated yield (DIAD=Diisopropyl azodicarboxylate).

Due to the low yields and the impractical separation of the desired product 10 from the double homologation product, we reconsidered our retrosynthetic approach. In our second generation retrosynthesis we shifted the bonds formed via lithiation-borylation chemistry by one carbon atom each, making middle fragment 13 and mono-Zweifel product 14 the new target molecules (Scheme 4).

Scheme 4. Second generation retrosynthetic analysis of georatusin (1).

For the synthesis of the new middle fragment 13, (α)-pseudoephedrine (16) was propionated. 23,24 Then, the (R)-Roche ester (18) was transformed into iodide 19 in a known three step sequence. 25 A literature known sequence consisting of Myers alkylation and reductive removal of the auxiliary gave us the corresponding alcohol 26 which was then converted into middle fragment 13 using a Mitsunobu reaction 22 (Scheme 5).

Scheme 5. Synthesis of middle fragment 13.
With middle fragment 13 and our mono-Zweifel product 14 in hands, we investigated the new fragment coupling using lithiation-borylation chemistry. Secondary alcohol 20 was isolated in a good yield of 64% over two steps. The following hydrogenation with Wilkinson’s catalyst proceeds smoothly to give us 21. Our first intention was a PMB protection of secondary alcohol 21 that could not be performed employing different conditions. So, a two-step sequence of TIPS-protection and selective TBS-deprotection led to primary alcohol 22 (Scheme 6). With alcohol 22 in hands, next in line was another TIB-esterification but unfortunately the best result we could achieve was a yield of 31% (Table 3). Higher temperatures for the Mitsunobu reaction as well as usage of TIB chloride led to decomposition.

![Scheme 6. Second generation fragment coupling.](image)

**Table 3. Conditions for the second TIB-esterification**

| Entry | Conditions | Reagent | Result |
|-------|------------|---------|--------|
| 1     | 22 (1.0 equiv.), PPh₃ (1.0 equiv.), DIAD (1.1 equiv.), THF, 0 °C to rt, 3 d | TIBOH (1.0 equiv.) | 31% |
| 2     | 22 (1.0 equiv.), PPh₃ (1.0 equiv.), DIAD (1.1 equiv.), THF, 0 °C to 50 °C, o/n | TIBOH (1.0 equiv.) | 10% |
| 3     | 22 (1.0 equiv.), NaH (1.5 equiv.), THF, 0 °C to 90 °C, o/n | TIBCl (1.5 equiv.) | decomp. |
| 4     | 22 (1.0 equiv.), NaH (1.5 equiv.), THF, 0 °C to 50 °C, o/n | TIBCl (1.5 equiv.) | decomp. |

**Conclusions**

In conclusion, we have developed a rapid access to complex, highly reduced polyketide fragments using lithiation-borylation chemistry and our developed mono-Zweifel protocol. With our strategy we were able to...
synthesize the C18-C27 fragment of the polyketide-peptide hybrid georatusin (1) in 8% over twelve steps in the longest linear sequence. Completion of the synthesis will be reported in due course.

**Experimental Section**

**General.** Unless otherwise noted all reactions were carried out under an argon atmosphere using a Drierite™ gas-drying unit. The used glassware was flame dried under high vacuum. Air- and moisture-sensitive liquids and solutions were transferred via syringe flushed with argon prior to use. All reagents were purchased from commercial suppliers and used without further purification unless otherwise noted. Stated temperatures, except room temperature, refer to bath temperatures.

Dry solvents: Dichloromethane and all amine bases were distilled under an inert atmosphere over calcium hydride. Tetrahydrofuran, diethyl ether, methanol and 1,2-dichloroethane were purchased from Acros Organics over molecular sieves and under inert atmosphere. Benzene was bought from Sigma Aldrich.

(+)-Sparteine was purchased from Chem-Impex and was distilled under high vacuum and stored under argon at −25 °C.

Thin layer chromatography: All reactions were stirred magnetically and monitored using pre-coated TLC sheets ALUGRAM® Xtra SIL G/UV254 (0.2 mm, silica gel, F254, aluminum-backed, MACHEREY-NAGEL) with detection by UV light (λ = 254 nm) and/or by staining with either basic potassium permanganate, acidic ceric ammonium molybdate or acidic vanillin stain. Flash column chromatography was performed using silica gel (0.04-0.063 mm, 240-400 mesh) obtained from MACHEREY-NAGEL. The applied petroleum ether fraction had a bp of 40-60 °C. The eluent is given in volume ratios (v/v).

1H-NMR experiments were recorded in CDCl3 using either a DPX 400 (Bruker), an AMX 400 (Bruker), an Ascend 400 Avance III HD (Bruker) or an Ascend 600 MHz (Bruker). The spectra were calibrated using the residual solvent peak: δ(CDCl3) = 7.26 ppm. Chemical shift δ is given in parts per million (ppm), coupling constant J in hertz (Hz) and multiplicity as follows: s, singlet; d, doublet; t, triplet; q, quadruplet; p, pentett; sex, sextet; sep, septet; m, multiplet; mC, centered multiplet; bs, broad signal or combination of these acronyms. NMR spectra were processed using TopSpin (Bruker).

13C-NMR experiments were recorded in CDCl3 using either a DPX 400 (Bruker), an AMX 400 (Bruker), an Ascend 400 Avance III HD (Bruker) or an Ascend 600 MHz (Bruker). The spectra were calibrated using the residual solvent peak: δ(CDCl3) = 77.16 ppm. Chemical shift δ is given in parts per million (ppm). NMR spectra were processed using TopSpin (Bruker).

High Resolution Mass Spectra (HRMS) were obtained either using a Q-Tof Premier (Waters), a LCT Premier (Waters) or a GC-system Agilent 6890 coupled with an Agilent 5973. Both the masses found and the masses calculated are given.

Melting points were determined in °C using an OptiMelt MPA 100 (Stanford Research System). Optical rotation [α]D was measured either on a P3000 polarimeter (A. Krüss Optronic, λ = 589 nm) or a Perkin Elmer 341 (λ = 589 nm). The sample concentration (in g/100 mL) is given with every single experiment.

Chiral HPLC was performed on a Merck/Hitachi L-7150 system with a Merck/Hitachi L-7400 UV-detector using a Daicel Chiralcel® OD-H column (4.6 x 250 mm, 5 μm). Further information can be found in the individual procedure.

The names of the compounds not shown were created using ChemDraw 19.1.
Ethyl 2,4,6-triisopropylbenzoate (24). A solution of TIBOH (6, 10.0 g, 40.3 mmol, 1.0 equiv.) in CHCl₃ (200 mL) was treated with a solution of NaOH (4.99 g, 125 mmol, 3.1 equiv.) and nBu₄NHSO₄ (1.09 g, 3.22 mmol, 8 mol%) in H₂O (160 mL). After addition of ethyl bromide (15.0 mL, 21.9 g, 201 mmol, 5.0 equiv.) the biphasic reaction mixture was stirred overnight at rt. The phases were separated and the aqueous phase was extracted with CH₂Cl₂ (3x). The combined organic phases were dried over Na₂SO₄ and concentrated in vacuo. The resulting oil was filtered through a short plug of silica using petroleum ether (PE):EtOAc (9:1) as eluent. The solvent was removed under reduced pressure to afford ethyl 2,4,6-triisopropylbenzoate (24, 10.8 g, 38.9 % yield 95%) as a yellow oil.

1H-NMR (400 MHz, CDCl₃): δ = 7.00 (s, 2H), 4.37 (q, J = 7.1 Hz, 2H), 2.87 (m, 3H), 1.37 (t, J = 7.1 Hz, 3H), 1.25 (d, J = 7.0 Hz) and 1.24 (d, J = 7.0 Hz, 18H) ppm; 13C-NMR (101 MHz, CDCl₃): δ = 171.0, 150.2, 144.9, 130.8, 121.0, 60.9, 34.6, 31.6, 24.3, 24.1, 14.4 ppm; HRMS (ESI): C₁₈H₂₈O₂Na [M+Na]⁺ calculated: 299.1987, found: 299.1986; Rf = 0.6 (PE:EtOAc 10:1, UV, KMM 2004).

Analytical data are in accordance with the literature.

Stannane 7. Ethyl 2,4,6-triisopropylbenzoate (24, 5.00 g, 18.1 mmol, 1.0 equiv.) and (-)-sparteine (5.4 mL, 55.1 g, 23.5 mmol, 1.3 equiv.) were dissolved in Et₂O (90 mL) in a 3-necked flask equipped with a magnetic stirrer. Et₃SnCl (1.0  m in hexanes, 18.0 mL, 23.5 mmol, 1.3 equiv., 0.5 mL/min , color change: colorless → brown/purple) was added and the reaction mixture stirred for 5 h at this temperature. Then a freshly prepared solution of Me₂SnCl (1.0  m in Et₂O, 23.5 mL, 23.5 mmol, 1.3 equiv.) was added dropwise (color change: brown/purple → yellow/colorless) and the reaction mixture was stirred for 1 h at 40 °C before being warmed to rt. After 30 min at rt 5% aq. H₃PO₄ was added and the biphasic mixture was stirred for further 20 min. The organic layer was separated and washed with 5% aq. H₃PO₄ (3x). The combined aqueous layers were extracted with Et₂O (3x). The organic layers were combined, dried over Na₂SO₄ and concentrated in vacuo to afford a slightly yellow solid, which was then recrystallized from MeOH (3 mL/g) to give stannane 7 (5.55 g, 12.7 mmol, 70%, er 99:1) as colorless needles. The racemic sample was prepared by the use of tetramethylethylenediamine (TMEDA) instead of (-)-sparteine.

Sparteine-recovery: After adjusting the pH of the combined aqueous phases to 11 by using aq. 2.0 M NaOH, they were extracted with Et₂O (3x). The organic layers were combined, dried over K₂CO₃ and concentrated in vacuo. The residue was then distilled under high vacuum over calcium hydride (100 mg/g) at 150 °C to afford the respective enantiomer of sparteine (70-80%) as a colorless oil, which solidified in the freezer.

1H-NMR (400 MHz, CDCl₃): δ = 6.99 (s, 2H), 5.08-5.00 (m, 1H), 2.92-2.80 (m, 3H), 1.68-1.51 (m, 3H), 1.24 (d, J = 6.9 Hz, 18H), 0.18 (s, d, J = 54.2 Hz and J = 51.6 Hz, 9H) ppm; 13C-NMR (101 MHz, CDCl₃): δ = 171.4, 150.1, 145.0, 130.9, 120.9, 67.2, 34.5, 31.5, 24.5, 24.2, 24.1, 19.4 ppm. Calculated: 463.1635, found: 463.1634; Rf = 0.9 (PE:EtOAc 95:5); [α]D = 42.0 (c 1.0, CHCl₃); m.p. = 65 °C Chiral HPLC: (Daicel Chiracel® OD-H column (25 cm), hexanes, 0.7 mL/min, rt, 210 nm): tR = 6.4 min (S), 14.6 min (R), er 1:99.
Analytical data are in accordance with the literature.\textsuperscript{18,28}

**1,3-Bis(boronic ester) 3.** Following Aggarwal's procedure\textsuperscript{18}, a stirred solution of stannane 7 (5.00 g, 11.4 mmol, 2.05 equiv.) in Et\textsubscript{2}O (57 Y[\textsuperscript{X}X\textsubsuperscript{2}][\textsuperscript{Y}X\textsubsuperscript{2}]) was treated with nBuLi (1.6 M in hexanes, 7.0 mL, 11.1 mmol, 2.0 equiv., 0.5 mL/min). The reaction mixture was stirred for 1.5 h at this temperature. Then a solution of pinBCH\textsubscript{2}Bpin\textsuperscript{29} (1.49 g, 5.56 mmol, 1.0 equiv., 0.5 mL/min) in Et\textsubscript{2}O (11.0 mL) was added. After 2.5 h at this temperature, the reaction mixture was warmed to rt and stirred overnight. H\textsubscript{2}O and Et\textsubscript{2}O were added and the organic layer was separated. The aqueous phase was extracted with Et\textsubscript{2}O (3x), the organic layers were combined and dried over Na\textsubscript{2}SO\textsubscript{4}. The solvent was removed \textit{in vacuo} and the crude material purified by flash column chromatography (PE:EtOAc 98:2) to afford C\textsubscript{2}-symmetric 1,3-bis(boronic ester) 3 (1.47 g, 4.54 mmol, 82\%, d.r \times 95:5), as a colorless oil.

\textsuperscript{1}H-NMR (400 MHz, CDCl\textsubscript{3}): \(\delta = 1.42\) (t, J = 7.8 Hz, 2H), 1.23 (s, 24H), 1.12-1.03 (m, 2H), 0.93 (d, J = 7.4 Hz, 6H) ppm; \textsuperscript{13}C-NMR (101 MHz, CDCl\textsubscript{3}): \(\delta = 82.9, 36.1, 24.90, 24.89, 15.5\) ppm (carbon attached to boron not observed); HRMS (ESI): \(\text{C}_{12}\text{H}_{34}\text{B}_{2}\text{O}_{4}\text{Na}[\text{M+Na}]^+\) calculated: 347.2541, found: 347.2542; \(R_f = 0.3\) (PE:EtOAc 9:1, CAN); \([h\textsubscript{\text{d}}\textsuperscript{20}] = +10.5\) (c 1.0, CHCl\textsubscript{3}); Analytical data are in accordance with the literature.\textsuperscript{18}

**Mono-Zweifel product 14.** To a stirred solution of 1,3-bis(boronic ester) 3 (100 mg, 0.31 mmol, 1.0 equiv.) in THF (1.5 Y[\textsuperscript{X}X\textsubsuperscript{2}][\textsuperscript{Y}X\textsubsuperscript{2}]) was added vinylMgBr (1.0 M in THF, 0.52 mL, 0.52 mmol, 1.7 equiv., 0.5 mL/min) and stirring was continued for 30 min at this temperature. Then the solution was warmed to rt and stirred for further 30 Y[\textsuperscript{X}X\textsubsuperscript{2}][\textsuperscript{Y}X\textsubsuperscript{2}]\textsuperscript{2}]. iodine (313 mg, 1.23 mmol, 4.0 equiv.) was added in two portions over a period of 5 min. MeOH (2.5 mL, 0.15 mL/min) was added to the dark solution and the reaction mixture was stirred for 30 min. Then, a suspension of NaOMe (1.0 M in MeOH, 2.5 mL, 2.50 mmol, 8.0 equiv., 0.5 mL/min) was added and the red reaction mixture was stirred for further 30 Y[\textsuperscript{X}X\textsubsuperscript{2}][\textsuperscript{Y}X\textsubsuperscript{2}]\textsuperscript{2}]. After warming to rt, the black reaction mixture was stirred overnight. Methyl \textit{t}ert-butyl ether (MTBE) and sat. aq. Na\textsubscript{2}SO\textsubscript{4} were added until the dark color disappeared. The phases were separated and the aqueous phase was extracted with MTBE (3x). The combined organic phases were washed with sat. aq. NaCl and dried over Na\textsubscript{2}SO\textsubscript{4}, \textit{concentrated in vacuo} and the crude residue was purified by flash column chromatography (PE:MTBE 98:2 \(\rightarrow\) 9:1) to afford mono-Zweifel product 14 (33 mg, 0.15 mmol, 48\%, 94\% brsm\textsuperscript{[a,b]}) as a yellow oil and reisolated 1,3-bis(boronic ester) 3 (48 mg, 0.15 mmol) as a slightly yellow oil.

\textsuperscript{[a]} At a 5.99 mmol scale (1.94 g) of 1,3-bis(boronic ester) 3 mono-Zweifel product 14 was obtained in 35\% (470 mg, 2.10 mmol, 81\% brsm).

\textsuperscript{[b]} After three cycles mono-Zweifel product 14 was obtained in 62\% (831 mg, 3.71 mmol).

\textsuperscript{1}H-NMR (400 MHz, CDCl\textsubscript{3}): \(\delta = 5.68\) (m, 1H), 4.98-4.87 (m, 2H), 2.23-2.12 (m, 1H), 1.49-1.41 (m, 1H), 1.30-1.25 (m, 1H), 1.24 (s, 12H), 1.12-1.03 (m, 1H), 0.98-0.92 (m, 6H) ppm; \textsuperscript{13}C-NMR (101 MHz, CDCl\textsubscript{3}): \(\delta = 145.2, 112.6,
82.9, 40.4, 37.2, 24.90, 24.85, 20.3, 15.8 ppm (carbon attached to boron not observed); HRMS (El): C_{13}H_{25}BO_{2} [M]^{+} calculated: 224.1948, found: 224.1947; R_{f} = 0.4 (PE: TBE 97:3, KM nO_{4}); [\theta_{D}20]^{o} = +14.5 (c 1.2, CHCl_{3}).

Analytical data are in accordance with the literature.\textsuperscript{4}

**Alcohol 8.** Mono-Zweifel product 14 (90.0 mg, 0.40 mmol, 1.0 equiv.) and bromochloromethane (0.08 mL, 156 mg, 1.20 mmol, 3.0 equiv.) were dissolved in Et_{2}O (2.0 mL). \[\text{HRMS (EI): C_{15}H_{30}BO_{2} [M]+Na}^{+} = 286.2095; R_{f} = 0.7 (PE:MTBE 97:3, KM nO_{4}); [\theta_{D}20]^{o} = +6.3 (c 1.0, CHCl_{3}).\]

**Carbamate 9.** A solution of alcohol 8 (200 mg, 1.56 mmol, 1.0 equiv.) in 1,2-dichloroethane (5.2 mL) was treated with Et_{3}N (0.32 mL, 2.34 mmol, 1.5 equiv.) and CbCl (383 mg, 2.34 mmol, 1.5 equiv.). The reaction mixture was stirred overnight at 70°C. H_{2}O and CH_{2}Cl_{2} were added, the phases were separated and the aqueous phase was extracted with CH_{2}Cl_{2} (3 x). The combined organic layers were dried over Na_{2}SO_{4} and concentrated in vacuo. The crude product was purified by flash column chromatography (pentane:Et_{2}O 5:1) to afford alcohol 8 (35 mg, 0.27 mmol, 68% 02s) as a colorless oil.\textsuperscript{1}

**TIB ester 11.** Alcohol 8 (300 mg, 2.34 mmol, 1.0 equiv.) was dissolved in anhydrous THF (7.8 mL) and PPh\textsubscript{3} (614 mg, 2.34 mmol, 1.0 equiv.) and TIBOH (6, 639 mg, 2.57 mmol, 1.1 equiv.) were added successively. After cooling to 0°C, DIAD (0.51 mL, 2.57 mmol, 1.1 equiv., 0.12 mL/min) was added, the reaction mixture was slowly warmed to rt and stirred overnight at that temperature. Et_{2}O and sat. aq. NaHCO\textsubscript{3} were added and the phases separated. The aqueous phase was extracted with Et_{2}O (3 x), the organic layers combined and dried over Na_{2}SO_{4}. The solvent was removed in vacuo to leave a crude oil, which was then triturated with PE. The white suspension was filtered through a short plug of silica using PE:EtOAc (9:1) as eluent. The solvent was removed under reduced pressure and the residue was further purified by flash column chromatography (PE:EtOAc 98:2) to afford TIB ester 11 (792 mg, 2.21 mmol, 94%) as a colorless oil.\textsuperscript{1}
1,4-bis(boronic ester) 10. To a stirred solution of TIB ester 11 (78 mg, 0.22 mmol, 1.0 equiv.) and (+)-sparteine (0.08 mL, 0.35 mmol, 1.6 equiv.) in Et2O (1.1 \( \gamma \)) was added sBuLi (1.3 m in hexanes, 0.25 mL, 0.32 mmol, 1.5 equiv., 0.5 mL/min). The brown reaction mixture was stirred for 5 h at that temperature before a solution of 1,3-bis(boronic ester) 3 (105 mg, 0.32 mmol, 1.5 equiv.) in Et2O (0.43 mL, 0.5 mL/min) was added. After stirring for further 1 K\( \ell \) at \( \gamma \) °C, the yellow reaction mixture was warmed to rt and stirred overnight. The reaction mixture was cooled to rt and HCl (2.0 M) was added and the biphasic mixture was stirred for 10 min. The phases were separated, the organic layer was washed with HCl (2.0 M, 3x) and the combined aqueous phases were extracted with Et2O (3x). The combined organic phases were dried over Na2SO4 and concentrated in vacuo. The crude material was purified by flash column chromatography (PE → PE:EtOAc 200:1 → 100:1 → 98:2 → 95:5) to afford 1,4-bis(boronic ester) 10 (37 mg, 0.09 mmol, 41%, dr \( \chi \) 95.5) as a colorless oil.

\( ^1 \)-H-NMR (400 MHz, CDCl3): \( \delta = 5.82-5.72 \) (m, 1H), 4.98-4.82 (m, 2H), 2.26-2.16 (m, 1H), 1.84-1.72 (m, 2H), 1.31-1.27 (m, 2H), 1.26-1.20 (m, 24H), 1.19-1.08 (m, 4H), 0.97-0.90 (m, 6H), 0.88-0.83 (m, 6H) ppm; \( ^{13} \)-C-NMR (101 MHz, CDCl3): \( \delta = 146.3, 111.2, 82.8, 82.8, 43.9, 40.7, 35.2, 30.2, 29.4, 25.4, 25.1, 24.9, 24.9, 18.9, 18.6, 17.6, 15.7 \) ppm (carbon attached to boron not observed); HRMS (ESI): \( \frac{C_{25}H_{48}B_2O_4Na}{M+Na} \) calculated: 457.3636; found: 457.3636; \( R_f = 0.5 \) (PE:EtOAc 95:5, vanillin); \( \left[ \frac{b}{b} \right]^{20}_{D} \) of \( \gamma \) = 0.2, CHCl3).

Methyl (\( \gamma \))-3-((tert-butyldimethylsilyl)oxy)-2-methylpropanoate (25). (\( \gamma \))-Roche ester 18, 4.0 mL, 36.3 mmol, 1.0 equiv.) was dissolved in CH2Cl2 (360 mL) and the resulting solution was cooled to 0 °C. Imidazole (3.70 g, 54.4 mmol, 1.5 equiv.) and TBSCI (6.56 g, 43.5 mmol, 1.2 equiv.) were added successively and stirring was continued for 30 min at 0 °C. After warming to rt the reaction mixture was stirred for 2 h before sat. aq. NH4Cl and H2O were added. The phases were separated and the aqueous phase was extracted with CH2Cl2 (3x). The combined organic phases were dried over Na2SO4 and concentrated under reduced pressure. The crude material was purified by flash column chromatography (PE:EtOAc 15:1) to afford Methyl (\( \gamma \))-3-((tert-butyldimethylsilyl)oxy)-2-methylpropanoate (25, 8.03 g, 34.6 mmol, 95%) as a colorless oil.

\( ^1 \)-H-NMR (600 MHz, CDCl3): \( \delta = 3.78-3.76 \) (m, 1H), 3.67-3.63 (m, 4H), 2.65 (m, 1H), 1.13 (d, \( J = 7.0 \) Hz, 3H), 0.87 (s, 9H), 0.04-0.03 (m, 6H) ppm; \( ^{13} \)-C-NMR (151 MHz, CDCl3): \( \delta = 75.1, 50.0, 26.8, 23.4, 18.3, 15.9, 9.3, 3.4, 2.2 \) ppm; HRMS (ESI): \( \frac{C_{11}H_{24}O_4SiNa}{M+Na} \) calculated: 255.1392, found: 255.1391; \( R_f = 0.6 \) (PE:EtOAc 10:1, KMnO4); \( \left[ \frac{b}{b} \right]^{20}_{D} \) of \( \gamma \) = 1.0, CHCl3).

Analytical data are in accordance with the literature.25

(S)-3-((tert-butyldimethylsilyl)oxy)-2-methylpropan-1-ol (26). Methyl (\( \gamma \))-3-((tert-butyldimethylsilyl)oxy)-2-methylpropanoate (25, 4.00 g, 17.2 mmol, 1.0 equiv.) was dissolved in CH2Cl2 (85 mL) and the resulting solution \( \delta = 35.8 \) °C. After the addition of DiBAI-H (1.0 M in CH2Cl2, 43 mL, 43.0 mmol, 2.5 equiv., 0.8 mL/min), HCl (40 g, 1.0 M) was added and the reaction mixture was stirred at that temperature for 3.5 h. MeOH (8.5 mL) and sat. aq. potassium sodium tartrate (105 mL) were slowly added. After warming to rt, the mixture was stirred vigorously overnight. The phases were separated and the aqueous phase was extracted with CH2Cl2 (3x). The combined organic phases were dried over Na2SO4 and concentrated in vacuo to give (S)-3-((tert-butyldimethylsilyl)oxy)-2-methylpropan-1-ol (26, 3.25 g, 15.9 mmol, 92%) as a colorless oil.

\( ^1 \)-H-NMR (600 MHz, CDCl3): \( \delta = 3.74 \) (m, 1H), 3.66-3.58 (m, 2H), 3.54 (m, 1H), 2.80 (m, 1H), 1.94 (m, 1H), 0.90 (s, 9H), 0.83 (d, \( J = 7.0 \) Hz, 3H), 0.07 (s, 6H) ppm; \( ^{13} \)-C-NMR (151 MHz, CDCl3): \( \delta = 69.0, 68.5, 37.2, 26.0, 18.3, 15.9 \) ppm; HRMS (ESI): \( \frac{C_{10}H_{23}O_2SiNa}{M+Na} \) calculated: 227.1443, found: 227.1442; \( R_f = 0.4 \) (PE:MTBE 10:1, KMnO4); \( \left[ \frac{b}{b} \right]^{20}_{D} \) of \( \gamma \) = 1.0, CHCl3).

Analytical data are in accordance with the literature.25

Iodide 19. In the darkness, a solution of the obtained (S)-3-((tert-butyldimethylsilyl)oxy)-2-methylpropan-1-ol (26, 1.50 g, 7.34 mmol, 1.0 equiv.) in CH2Cl2 (15.0 mL) was treated with PPh3 (2.50 g, 9.54 mmol, 1.3 equiv.)
and imidazole (0.75 g, 11.0 mmol, 1.5 equiv.) successively. After cooling to 0 °C, iodine (2.51 g, 9.91 mmol, 1.35 equiv.) was added in eight portions over a period of 30 min. The reaction mixture was warmed to rt and stirred for further 2.5 h before being quenched at 0 °C by the addition of sat. aq. Na2S2O3. The phases were separated and the aqueous phase was extracted with CH2Cl2 (3x). The combined organic phases were washed with sat. aq. Na2S2O3 (2x), dried over Na2SO4 and concentrated in vacuo. The crude material was purified by flash column chromatography (PE:Et2O 95:5) to afford iodide 19 (1.90 g, 6.05 mmol, 82%) as a slightly yellow oil. The iodide was used in the next step without detailed characterization.

\((2S,4S)-5-(\text{tert-butyldimethylsilyl})\text{oxy})-N-(\text{1R,2R})-1\text{-hydroxy-1-phenylpropan-2-yl})-N,2,4\text{-trimethylpentanamide (27)}\). Lithium chloride (3.08 g, 72.6 mmol, 13.5 equiv.) was flame dried under high vacuum and purged with argon. Then, THF (22.5 mL) and diisopropylamine (3.0 mL, 21.5 mmol, 4.0 equiv.) were added. After 20.6 °C, the reaction mixture was stirred for 10 min at this temperature before being warmed to 0 °C and stirred for further 10 min. The iodide was used in the next step without detailed characterization.

\((2S,4S)-5-(\text{tert-butyldimethylsilyl})\text{oxy})-2,4\text{-dimethylpentan-1-ol (28)}\). To a stirred solution of diisopropylamine (3.1 mL, 22.2 mmol, 4.3 equiv.) in THF (21.0 mL) was added nBuLi (1.6 m in hexanes, 13.0 mL, 20.6 mmol, 4.0 equiv.) at −78 °C. After stirring for 10 min at this temperature, the solution was warmed to 0 °C and stirred for further 10 min. Then borane-ammonia complex (0.72 g, 23.2 mmol, 4.5 equiv.) was added in three portions over a period of 5 min and the reaction mixture was allowed to stir for 15 min at 0 °C before being warmed to rt and stirred for 4.5 h at that temperature before being cooled to 0 °C. Sat. aq. NH4Cl and EtOAc were added at 0 °C and the organic layer was separated. The aqueous layer was extracted with EtOAc (3x). The combined organic layers were washed with sat. aq. NaCl and dried over Na2SO4. The solvent was removed in vacuo and the crude material was purified by flash column chromatography (PE:EtOAc 7:1) to afford \((2S,4S)-5-(\text{tert-butyldimethylsilyl})\text{oxy})-N-(\text{1R,2R})-1\text{-hydroxy-1-phenylpropan-2-yl})-N,2,4\text{-trimethylpentanamide (27)}\) as a colorless oil (mixture of amide bond rotamers, 4.5:1, NMR), which was directly used in the next step without further characterization.
1.17 g, 4.73 mmol, 1.1 equiv.) were added successively. After cooling to 0 °C, DIAD (0.93 mL, 4.73 mmol, 1.1 equiv., 0.12 mL/min) was added, the reaction mixture was slowly warmed to rt and stirred overnight at that temperature. Et₂O and sat. aq. NaHCO₃ were added and the phases were separated. The aqueous phase was extracted with Et₂O (3x), the combined organic layers were dried over Na₂SO₄. The solvent was removed in vacuo to leave a crude oil which was then triturated with PE. The white suspension was filtered through a short plug of silica using PE:EtOAc (9:1) as eluent. The solvent was removed under reduced pressure and the crude material was further purified by flash column chromatography (PE:EtOAc 99:1) to afford TIB ester 13 (1.79 g, 3.75 mmol, 87%) as a colorless oil.

1H-NM R (400 M Hz, CDCl₃): δ = 7.00 (s, 2H), 4.13 (dd, J = 6.3, 2.4 Hz, 2H), 3.40 (m, 2H), 2.94-2.80 (m, 3H), 2.02-1.94 (m, 1H), 1.75-1.67 (m, 1H), 1.31-1.14 (m, 20H), 0.96 (d, J = 6.7 Hz, 3H), 0.88 (s, 9H), 0.85 (d, J = 6.7 Hz, 3H), 0.03 (s, 6H) ppm; 13C-NM R (101 M Hz, CDCl₃): δ = 171.3, 150.1, 144.9, 130.9, 121.0, 70.8, 68.9, 37.1, 34.6, 33.1, 31.7, 30.1, δ 1.17 (m, 2H), δ 1.25 (m, 1H), δ 1.62 (s, 9H), δ 2.94 (m, 1H) ppm; HRMS (ESI): C₈₂H₂₀₂OSiNa [M +Na]⁺ calculated: 499.3583, found: 499.3582; Rf = 0.6 (PE:EtOAc 95:5, UV, KMnO₄); [η]D²⁰ = +10.6 (c 0.5, CHCl₃).

**Alcohol 20.** To a stirred solution of TIB ester 13 (450 mg, 0.94 mmol, 1.0 equiv.) and (+)-sparteine (0.35 mL, 1.51 mmol, 1.6 equiv.) in Et₂O (3.8 Y[X¹H][O²H][O³H] °C was added sBuLi (1.3 M in hexanes, 1.1 mL, 1.42 mmol, 1.5 equiv., 0.5 mL/min). The brown reaction mixture was stirred for 5 h at that temperature before a solution of mono-Zweifel product 14 (296 mg, 1.32 mmol, 1.4 equiv.) in THF (2.6 mL, 0.5 mL/min) was added. After stirring for further 2 °C/0° H, the yellow reaction mixture was warmed to 40 °C and stirred overnight. The reaction mixture was cooled to rt, aq. 5% H₃PO₄ was added and the biphasic mixture was stirred for 20 min. The phases were separated, the organic layer was washed with aq. 5% H₃PO₄ (3x) and the combined aqueous phases were extracted with MTBE (3x). The combined organic phases were dried over Na₂SO₄ and concentrated in vacuo. The orange residue was dissolved in THF (4.8 Y[X⁴H][O⁵H][O⁶H] °C. A premixed solution of NaOH (2.0) / H₂O (35%, 2/1 v/v, 3.8 mL) was added dropwise. The reaction mixture was stirred for 2 h at rt before being quenched by the addition of sat. aq. Na₂SO₄ at 0 °C. The solution was diluted with MTBE, the phases were separated and the aqueous phase was extracted with MTBE (3x). The combined organic layers were dried over Na₂SO₄ and concentrated in vacuo. The crude product was purified by flash column chromatography (PE:EtOAc 97:3 → 95:5) to afford alcohol 20 (207 mg, 0.60 mmol, 64% o2s, δ x 95:5) as a colorless oil.

1H-NM R (400 M Hz, CDCl₃): δ = 5.68 (m, 1H), 4.97-4.89 (m, 2H), 3.41 (d, J = 6.5 Hz, 2H), 3.17-3.15 (m, 1H), 2.24 (m, 1H), 1.78-1.59 (m, 3H), 1.50 (bs, 1H), 1.41-1.32 (m, 2H), 1.25-1.17 (m, 2H), 0.97 (d, J = 6.6 Hz, 3H), 0.90 (s, 9H), 0.86-0.80 (m, 9H), 0.05 (s, 6H) ppm; 13C-NM R (101 M Hz, CDCl₃): δ = 145.3, 112.5, 78.6, 69.7, 41.2, 36.5, 35.3, 33.7, 33.2, 32.2, 26.1, 20.4, 18.6, 16.7, 16.1, 13.3, 65.2 ppm; HRMS (ESI): C₂₀H₄₂O₃SiNa [M +Na]⁺ calculated: 365.2852, found: 365.2849; Rf = 0.3 (PE:EtOAc 95:5, vanillin); [η]D²⁰ = +9.2 (c 0.5, CHCl₃).

**Alcohol 21.** Through a solution of Wilkinson’s catalyst (108 mg, 0.12 mmol, 20 mol%) in benzene (3.0 mL) were bubbled three balloons of H₂. The dark red solution was stirred for 1.5 h at rt under an atmosphere of H₂ while the solution turned orange to yellow. After the addition of alcohol 20 (200 mg, 0.58 mmol, 1.0 equiv.) in PhH (3.0 mL), the reaction mixture was stirred overnight. The solvent was removed and the crude residue was purified by flash column chromatography (PE:EtOAc 98:2) to give alcohol 21 (190 mg, 0.55 mmol, 95%) as a colorless oil.

1H-NM R (400 M Hz, CDCl₃): δ = 3.40 (dd, J = 6.4, 1.1 Hz, 2H), 3.10 (m, 1H), 1.78-1.62 (m, 3H), 1.48-1.05 (m, 8H), 0.90 (s, 9H), 0.87-0.83 (m, 15H), 0.04 (s, 6H) ppm; 13C-NM R (101 M Hz, CDCl₃): δ = 80.6, 69.7, 41.5, 35.7, 33.4, 33.3, 32.3, 31.7, 30.5, 26.1, 19.1, 18.5, 16.5, 16.4, 13.1, 11.5, 65.2 ppm; HRMS (ESI): C₂₀H₄₂O₃SiNa [M +Na]⁺ calculated: 367.3008, found: 367.3008; Rf = 0.3 (PE:EtOAc 95:5, vanillin); [η]D²⁰ = +8.2 (c 0.6, CHCl₃).
(65,85,9R)-11,11-diisopropyl-2,2,3,3,6,8,12-heptamethyl-9-((2S,4R)-4-methylhexan-2-yl)-4,10-dioxa-3,11-disilatridecane (29). Alcohol 21 (90 mg, 0.26 mmol, 1.0 equiv.) was dissolved in CH₂Cl₂ (2.4 mL) and the solution was cooled to 8 °C. 2,6-Lutidine (0.18 mL, 1.57 mmol, 6.0 equiv.) and TIPSOTf (0.28 mL, 1.04 mmol, 4.0 equiv.) were added successively and the reaction mixture was warmed to rt and stirred at that temperature overnight. Sat. aq. NaHCO₃ and MTBE were added, the phases separated and the aqueous phase was extracted with MTBE (3x). The combined organic phases were washed with sat. aq. NaHSO₄ and sat. aq. NaHCO₃, dried over Na₂SO₄ and concentrated in vacuo. Further Purification of the crude material by flash column chromatography (PE) afforded (65,85,9R)-11,11-diisopropyl-2,2,3,3,6,8,12-heptamethyl-9-((2S,4R)-4-methylhexan-2-yl)-4,10-dioxa-3,11-disilatridecane (29, 128 mg, 0.26 YY% 95%) as a colorless oil.

Alcohol 22. To a stirred solution of (65,85,9R)-11,11-diisopropyl-2,2,3,3,6,8,12-heptamethyl-9-((2S,4R)-4-methylhexan-2-yl)-4,10-dioxa-3,11-disilatridecane (29, 120 mg, 0.24 mmol, 1.0 equiv.) in CH₂Cl₂/MeOH (1/1, v/v, 2.4 mL) was added PPTS (66 mg, 0.26 mmol, 1.1 equiv.). The reaction mixture was heated to 45 °C and stirred at that temperature for 1 h. Sat. aq. NaHCO₃ and EtOAc were added, the phases were separated and the aqueous phase was extracted with EtOAc (3x). The combined organic phases were dried over Na₂SO₄. The solvent was removed under reduced pressure and the crude material was further purified by flash column chromatography (PE:EtOAc 93:7) to afford primary alcohol 22 (80 mg, 0.21 mmol, 88%) as a colorless oil.

TIB ester 23. Alcohol 22 (50 mg, 0.13 mmol, 1.0 equiv.) was dissolved in anhydrous THF (0.43 mL) and PPh₃ (34 mg, 0.13 mmol, 1.0 equiv.) and TIBOH (6, 32 mg, 0.13 mmol, 1.0 equiv.) were added successively. After cooling to 0 °C, DIAD (28 µL, 0.14 mmol, 1.1 equiv.) was added, the reaction mixture was slowly warmed to rt and stirred for 3 d at that temperature. Et₂O and sat. aq. NaHCO₃ were added and the phases separated. The aqueous phase was extracted with Et₂O (3x), the organic layers combined and dried over Na₂SO₄. The solvent was removed in vacuo to leave a crude oil which was then triturated with PE. The white suspension was filtered through a short plug of silica using PE:EtOAc (9:1) as eluent. The solvent was removed under reduced pressure and the crude material was further purified by flash column chromatography (PE:EtOAc 98:2) to afford TIB ester 23 (25 mg, 0.04 mmol, 31%) as a colorless oil.
Acknowledgements

In terms of preparation of the manuscript we thank Alina Eggert and Daniel Lücke. We thank Dr. J. Fohrer, M. Rettstadt and D. Körtje for detailed 2D-NMR analysis and A. Schulz and R. Reichel for mass spectra. A generous gift of B$_2$pin$_2$ from Allychem is also appreciated.

Supplementary Material

$^1$H-NMR and $^{13}$C-NMR spectra associated with this article are available as supplementary data.

References

1. Ehrlich, G.; Hassfeld, J.; Eggert, U.; Kalesse, M. Chem. Eur. J. 2008, 14, 2232. [https://doi.org/10.1002/chem.200701529]
2. Brodmann, T.; Janssen, D.; Kalesse, M. J. Am. Chem. Soc. 2010, 132, 13610. [https://doi.org/10.1021/ja107290s]
3. Jahns, C.; Hoffmann, T.; Müller, S.; Gerth, K.; Washausen, P.; Höfle, G.; Reichenbach, H.; Kalesse, M.; Müller, R. Angew. Chem. Int. Ed. 2012, 51, 5239. [https://doi.org/10.1002/anie.201200327]
4. Rentsch, A.; Kalesse, M. Angew. Chem. Int. Ed. 2012, 51, 11381. [https://doi.org/10.1002/anie.201206560]
5. Hartmann, O.; Kalesse, M. Org. Lett. 2012, 14, 3064. [https://doi.org/10.1021/ol3011387]
6. Hartmann, O.; Kalesse, M. Angew. Chem. Int. Ed. 2014, 53, 7335. [https://doi.org/10.1002/anie.201402259]
7. Symkenberg, G.; Kalesse, M. Angew. Chem. Int. Ed. 2014, 53, 1795. [https://doi.org/10.1002/anie.201309386]
8. Gieseler, M. T.; Kalesse, M. Org. Lett. 2014, 16, 548. [https://doi.org/10.1021/ol403423r]
9. Tautz, T.; Hoffmann, J.; Hoffmann, T.; Steinmetz, H.; Washausen, P.; Kunze, B.; Huch, V.; Kitsche, A.; Reichenbach, H.; Höfle, G.; Müller, R.; Kalesse, M. Org. Lett. 2016, 18, 2560. [https://doi.org/10.1021/acs.orglett.6b00810]
10. Steinmetz, H.; Li, J.; Fu, C.; Zaburannya, N.; Kunze, B.; Harmrolfs, K.; Schmitt, V.; Herrmann, J.; Reichenbach, H.; Höfle, G.; Kalesse, M.; Müller, R. Angew. Chem. Int. Ed. 2016, 55, 10113. [https://doi.org/10.1002/anie.201603288]
11. Parthasarathy, G.; Eggert, U.; Kalesse, M. Org. Lett. 2016, 18, 2320. [https://doi.org/10.1021/acs.orglett.6b00814]
12. Gerstmann, L.; Kalesse, M. Chem. Eur. J. 2016, 22, 11210. [https://doi.org/10.1002/chem.201602682]
13. Poock, C.; Kalesse, M. Org. Lett. 2017, 19, 4536. [https://doi.org/10.1021/acs.orglett.7b02112]
14. Witte, S. N. R.; Hug, J.J.; Geraldy, M. N. E.; Müller, R.; Kalesse, M. Chem. Eur. J. 2017, 23, 15917.
https://doi.org/10.1002/chem.201703782
15. Surup, F.; Kuhnert, E.; Böhm, A.; Pendzialek, T.; Solga, D.; Wiebach, V.; Engler, H.; Berkessel, A.; Stadler, M.; Kalesse, M. Chem. Eur. J. 2018, 24, 2200. https://doi.org/10.1002/chem.201704928
16. Lücke, D.; Linne, Y.; Hempel, K.; Kalesse, M. Org. Lett. 2018, 20, 4475. https://doi.org/10.1021/acs.orglett.8b01768
17. Shi, Y.-M.; Richter, C.; Challinor, V. L.; Grün, P.; Girela Del Rio, A.; Kaiser, M.; Schüffler, A.; Piepenbring, M.; Schwalbe, H.; Bode, H. B. Org. Lett. 2018, 20, 1563. https://doi.org/10.1021/acs.orglett.8b00293
18. Blair, D. J.; Tanini, D.; Bateman, J. M.; Scott, H. K.; Myers, E. L.; Aggarwal, V. K. Chem. Sci. 2017, 8, 2898. https://doi.org/10.1039/C6SC05338F
19. Linne, Y.; Schönwald, A.; Weißbach, S.; Kalesse, M. Chem. Eur. J. 2020, 26, 7998. https://doi.org/10.1002/chem.202000599
20. Balieu, S.; Hallett, G. E.; Burns, M.; Bootwicha, T.; Studley, J.; Aggarwal, V. K. J. Am. Chem. Soc. 2015, 137, 4398. https://doi.org/10.1021/ja512875g
21. Stymiest, J. L.; Dutheuil, G.; Mahmood, A.; Aggarwal, V. K. Angew. Chem. Int. Ed. 2007, 46, 7491. https://doi.org/10.1002/anie.200702146
22. Mykura, R. C.; Veth, S.; Varela, A.; Dewis, L.; Farndon, J. J.; Myers, E. L.; Aggarwal, V. K. J. Am. Chem. Soc. 2018, 140, 14677. https://doi.org/10.1021/jacs.8b06871
23. Myers, A. G.; Yang, B. H.; Chen, H.; McKinstry, L.; Kopecky, D. J.; Gleason, J. L. J. Am. Chem. Soc. 1997, 119, 6496. https://doi.org/10.1021/ja970402f
24. Myers, A. G.; Yang, B. H.; Chen, H.; Kopecky, D. J. Synlett 1997, 5, 457. https://doi.org/10.1055/s-1997-6121
25. Hansen, D. A.; Rath, C. M.; Eisman, E. B.; Narayan, A. R. H.; Kittendorf, J. D.; Mortison, J. D.; Yoon, Y. J.; Sherman, D. H. J. Am. Chem. Soc. 2013, 135, 11232. https://doi.org/10.1021/ja404134f
26. Lowe, J. T.; Panek J. S., Org. Lett. 2008, 10, 3813. https://doi.org/10.1021/ol801499s
27. Beak, P.; Carter, L. G. J. Org. Chem. 1981, 46, 2363. https://doi.org/10.1021/jo00324a030
28. M. Burns, M.; Essafi, S.; Bame, J. R.; Bull, S. P.; Webster, M. P.; Balieu, S.; Dale, J. W.; Butts, C. P.; Harvey, J. N.; Aggarwal, V. K. Nature 2014, 513, 183. https://doi.org/10.1038/nature13711
29. pinBCH₂Bpin can be purchased from Allychem or prepared on multigram scale; see Hong, K.; Liu, X.; Morken, J. P. J. Am. Chem. Soc. 2014, 136, 10581. https://doi.org/10.1021/ja505455z

This paper is an open access article distributed under the terms of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/)