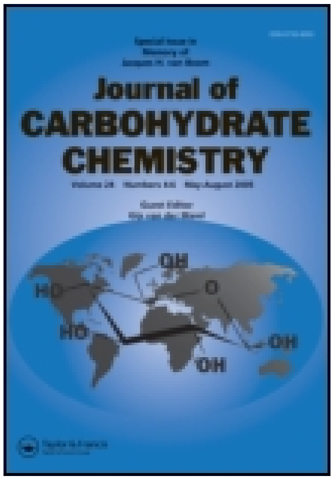

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The Selective Silylation of d-Mannitol Assisted by Phenylboronic Acid and the Solid State and Solution Structures of the Intermediate 1,6-bis(silyl) bis(phenylboronates)

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The Selective Silylation of D-Mannitol Assisted by Phenylboronic Acid and the Solid State and Solution Structures of the Intermediate 1,6-bis(silyl) bis(phenylboronates)

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ABSTRACT

The influence of phenylboronic acid on the silylation of D-mannitol by TBDMSCl and TBDPSCl has been investigated. Terminal silyation was found to dominate, with PBA significantly enhancing the yield of 1,6 di-TBDMS D-mannitol compared to the control. The intermediate 1,6-disilyl bis(phenylboronates) showed unusually high stability, such that oxidative conditions were required to cleave the boronate esters. X-ray crystal structures of both bis(phenylboronates) were determined, revealing both diboronate esters to exist as two fused six-membered rings. The results of ^{11}B NMR experiments suggest that these structures also predominate in solution, whereas the

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bis(phenylboronate) ester of D-mannitol itself exists as a mixture of five-membered and six-membered cyclic boronates.

Key Words: Silylation; Mannitol; Boronate; Phenylboronic acid; 1,3,2-Dioxaborolane.

INTRODUCTION

The use of boronic acids as protective agents in organic synthesis was pioneered by Ferrier and others in the 1960's and 70's,[1] and articles describing the use of boronic acids in this way, and as catalysts for a range of organic transformations, have appeared intermittently in the intervening years.[2] Our interest in the development of synthetic procedures that require minimal manipulation and purification steps led us to examine the selective terminal acylation and alkylation of open chain 1,2,3-triols, assisted by phenylboronic acid (PBA).[3] These reactions were carried out in a single pot, yielding analytically pure products in moderate yield, without the need for chromatography or formal recrystallisation steps. In some cases, PBA could be recovered for re-use. The structures of the intermediate boronate esters prior to and post derivatisation were not determined.[a]

Here we report an extension of this work to the selective 1,6-*silylation* of D-mannitol. We have found that the introduction of bulky, hydrophobic silyl ethers onto the terminal oxygens of D-mannitol results in a significant stabilisation of the intermediate diboronate esters such that recovery of the PBA after completion of the reaction sequence becomes difficult. However, this added stability has allowed us to determine the solid-state crystal structures of two intermediate silylated boronate esters, **1** and **2**.

RESULTS AND DISCUSSION

Silyation Reactions

Silyl ethers, particularly *tert*-butyldimethylsilyl ether (TBDMS) and *tert*-butyldiphenylsilyl ether (TBDPS) are used extensively in organic synthesis for the protection of hydroxyl groups.[5,6] Most procedures for the formation of these ethers involve the reaction of an alcohol with the appropriate silyl chloride in the presence of a base, such as imidazole. When the substrate is a polyol, regioselectivity is governed by a balance between the steric requirements of the bulky TBDMS or TBDPS groups and the nucleophilicity of the hydroxyl groups. The TBDMS protecting group is sometimes preferred over TBDPS due to its ease of removal. Procedures for the clean preparation

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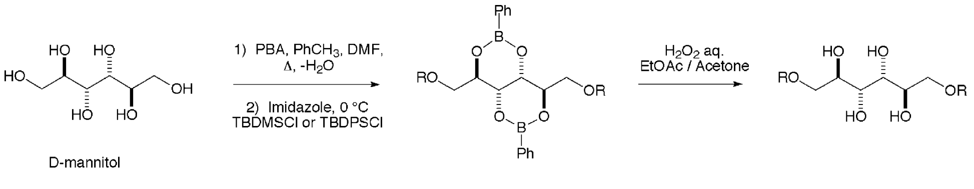
[a] The crystal structure of the bis(phenylboronate) of D-mannitol-1,6-dibenzoate, which had been prepared from D-mannitol by direct benzoylation *followed by* condensation with phenylboronic acid has recently been reported.[4]



1 R = TBDMS, *96%*
2 R = TBDPS, *54%*

3 R = TBDMS, *62%*
4 R = TBDPS, *62%*

Scheme 1. Preparation of D-mannitol 1,6-bis(silyl) bis(phenylboronates) and subsequent oxidative cleavage to D-mannitol 1,6-bis(silylethers).

of the 1,6-diTBDPS ether of D-mannitol (**4**) have been reported,[7,8] but not for the corresponding diTBDMS ether (**3**).

In the present study, solutions of the bis(phenylboronate) of D-mannitol[b] were prepared by azeotropic removal of water from a mixture of D-mannitol, two equivalents of phenylboronic acid (PBA), toluene and *N*,*N*-dimethylformamide (DMF). The toluene was then evaporated, the reaction mixture cooled to 0°C, and imidazole then the silyl chloride (TBDMSCl or TBDPSCl) was added. Extraction with dichloromethane followed by concentration yielded the pure, crystalline 1,6-bis(silyl) D-mannitol bis(phenylboronates) (**1** and **2**, Scheme 1). In contrast to the 1,6-bis(benzyl) and 1,6-bis(octanoyl) D-mannitol bis(phenylboronates) obtained in our previous study,[3] both the 1,6-bis(*tert*-butyldimethylsilyl) D-mannitol bis(phenylboronate) **1** and the 1,6-bis-(*tert*-butyldiphenylsilyl) D-mannitol bis(phenylboronate) **2** were found to be very stable towards alkaline hydrolysis. Other common techniques used for the cleavage of phenylboronates,[2] such as trans-esterification with neopentylglycol or pinacol also had no effect on **1** and **2**. Instead, the cleavage of these phenylboronates required oxidative conditions.[2] The presence of terminal bulky and lipophilic silyl groups clearly stabilises these bis-boronates towards nucleophilic attack from hydroxide and alcohols. Although the oxidation step, which employs hydrogen peroxide, is a very clean process, it precludes the recovery of PBA, as the boronates are converted irreversibly to phenol and the readily hydrolysed borates.

In order to evaluate the ability of PBA to enhance the selectivity of silylation of D-mannitol, identical silylation reactions were performed, with the omission of PBA. The crude reaction mixtures thus obtained were analysed using ^{1}H NMR spectroscopy and pre-calibrated electrospray mass spectrometry.[c] In the reaction that employed TBDMSCl as the silylating agent, a crude yield of 65% was obtained (cf. 96% for **1**), with two silylated products, the disilylated D-mannitol **3** and a tri-silyated D-mannitol, present in a ratio of 1.6:1.0, accounting for ~90% of the reaction mixture. In the reaction that employed TBDPSCl as the silylating agent, a crude yield of 78% was

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[b] For a preliminary discussion of the structure of the intermediate phenylboronate esters of D-mannitol see footnote 12 in Ref. [3].

[c] Relative peak intensities can give an indication of relative abundance of components in a mixture if the components give similar responses in the spectrometer and, as was the case here, there are few or no fragment ions.

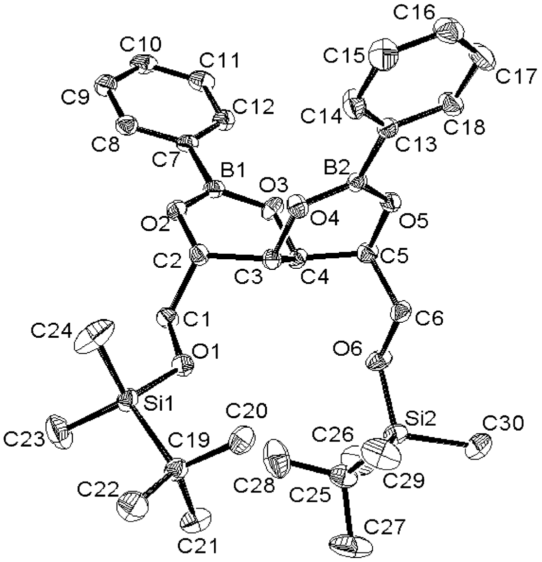

Figure 1. ORTEP view of **1** with 50% thermal ellipsoids.

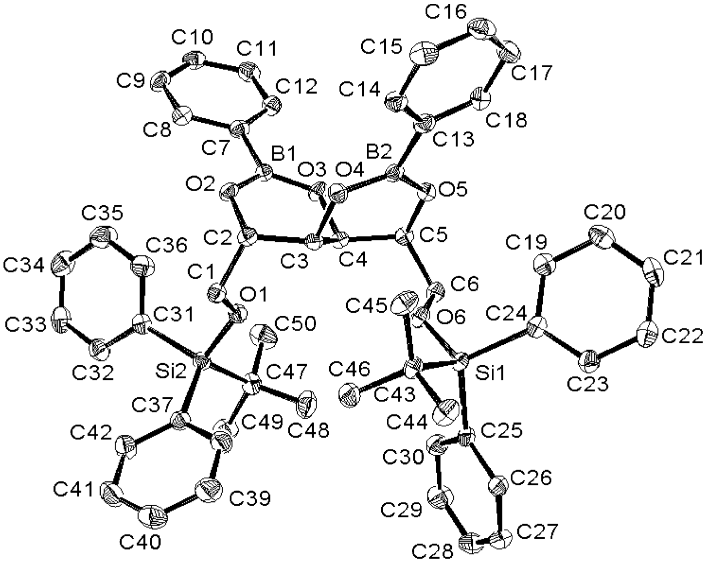

Figure 2. ORTEP view of **2** with 50% thermal ellipsoids. The two acetone molecules of crystallisation have been omitted for clarity.

Table 1. Selected bond angles (°) with standard deviations in parentheses for compounds **1** and **2**.

Bonds	**1**	**2**
C7B1O3	118.0(2)	119.0(2)
O3B1O2	123.0(2)	123.6(2)
O2B1C7	119.0(2)	117.4(2)
C13B2O5	118.8(2)	116.9(2)
O5B2O4	123.5(2)	123.8(2)
O4B2C13	117.7(2)	119.4(2)

obtained (cf. 54% for **2**), with two silylated products, the disilylated D-mannitol **4** and a tri-silylated D-mannitol present in a ratio of 10.0:1.0, accounting for ~85% of the reaction mixture. In contrast to these results, ^{1}H NMR, ^{13}C NMR and microanalysis of the crude products from both PBA-assisted reactions indicated that in those cases only bis-silylation had occured.

Solid State Structures of bis(Phenyl Boronates) 1 and 2

Relatively few crystal structures of cyclic trigonal aryl boronates formed from polyols with more than one potential diol binding site have so far been reported.[4,9–13] The structures obtained for **1** and **2** provide insight into their formation and an opportunity to expand the limited knowledge of the solid state structures of such compounds. Crystals of **1** suitable for x-ray analysis were obtained directly from the crude product of the PBA assisted silyation of D-mannitol with TBDMSCl. Single co-crystals of **2** with two moles of acetone were grown by slow evaporation of an acetone solution of the crude product of the PBA assisted silyation of D-mannitol with TBDPSCl. ORTEP diagrams and numbering schemes for **1** and **2** are shown in Figures 1 and 2 respectively.

Compounds **1** and **2** were found to have very similar solid state structures, with two six-membered dioxaboroline rings fused onto a mannitol backbone, and with two pseudo-tetrahedral silyl-ether substituents at the terminal positions. The coordination at all boron centres is distorted trigonal planar with mean bond angles over both structures being C–B–O 118.3(9)° and O–B–O 123.5(3)° (Table 1). The B–O interatomic

Table 2. Selected boron atom bond lengths (Å) with standard deviations in parentheses for **1** and **2**.

Bond	**1**	**2**
C7B1	1.560(2)	1.570(3)
B1O3	1.363(2)	1.366(2)
B1O2	1.365(2)	1.365(2)
C13B2	1.562(3)	1.566(3)
B2O5	1.369(2)	1.361(2)
B2O4	1.365(2)	1.372(2)

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Table 3. Dihedral angles (°) between selected mean planes for **1** and **2**.

Planes	**1**	**2**
1 vs. 2	86.1	86.1
1 vs. 3	4.9	8.4
2 vs. 4	4.2	5.1
5 vs. 3	9.1	9.4
5 vs. 1	5.7	3.5
6 vs. 4	2.3	6.6
6 vs. 2	3.3	4.5

See Table 4 for definition of planes.

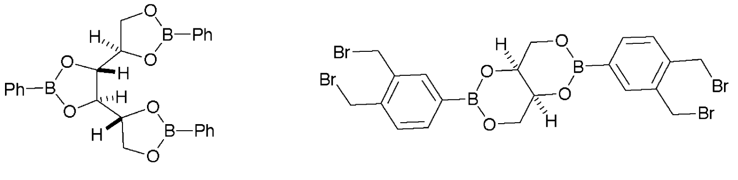
distances are typical for such trigonal aromatic boronates (1.361–1.372 Å, Table 2, compares with the Cambridge Structural Database mean B(3)–O(2) 1.367 Å)[14] as are the *ipso*-C–B bond lengths (1.560–1.570 Å, Table 2, compares with the Cambridge Structural Database mean B(3)-C*ar* 1.556 Å).[14] The six-membered rings in both structures are almost planar, with one atom, C3 for the ring containing B1, and C4 for the ring containing B2, lying slightly outside of the main plane. The mean planes defined by the aryl rings (Planes 1 and 2, Tables 3 and 4) diverge from the backbone with an angle of 86.1° for both **1** and **2**.

The high degree of co-planarity observed between the boronate aromatic rings and the corresponding planes defined by *ipso*-C–BO_2 (dihedral angles range from 4.2–8.4°, Table 3) in **1** and **2** indicate a general overlap of aromatic π-electrons with the vacant *p*-orbital of boron. This type of co-planarity has been observed in related boronates.[4,10,11,15]

The six-membered boronate rings observed for the solid state structures of **1** and **2** contrast with the three five-membered boronate rings observed in the tris(phenylboronate) ester of D-mannitol (**5**, Figure 3) which crystallizes exclusively from an aqueous methanol solution of D-mannitol and one or two equivalents of PBA.[9,16,17] The presence of six-membered boronate rings in **1** and **2** is, however, consistent with a similar solid state structure obtained by Shinkai and co-workers[11] of a 1:2 threitol-aryl boronic acid diester (**6**) which also showed exclusive formation of six-membered boronate rings. The presence of six-membered boronates in **1** and **2** is also consistent

Table 4. Definition of planes listed in Table 3.

Plane number	Definition
1	C7B1O2O3
2	C13B2O4O5
3	C7C8C9C10C11C12
4	C13C14C15C16C17C18
5	C2C3C4O3B1O2
6	C3C4C5O5B2O4



5 **6**

Figure 3. Tris(phenylboronate) ester formed from D-mannitol (**5**)[9] and bis(phenylboronate) ester formed threitol (**6**). (From Ref. [11].)

with the view that, due to ring strain, six-membered trigonal boronate esters are more stable, and hence more readily formed than five-membered esters.[1,2]

The IR spectra (KBr) for **1** and **2** show characteristic B–O absorption bands[18] at 1338 cm^{-1} and 1334 cm^{-1}, respectively, which are at lower frequencies to the B–O stretch for the tris(phenylboronate) ester of D-mannitol (**5**)[d] at 1355 cm^{-1}. These findings are also consistent with similar observations by Shinkai et al. [11] who found that the B–O stretch for a six-membered boronate appeared at a lower frequency than the B–O stretch for an electronically similar five-membered boronate.

Solution Structures of Phenylboronates Derived Directly or Indirectly from D-Mannitol

Shinkai et al.[11] have used ^{11}B NMR spectroscopy to great effect to characterise, in CDCl$_3$ solution, the ring size of the cyclic boronates present in **6**. They found that in electronically similar model compounds, the ^{11}B NMR signal for a five membered boronate occurred at a chemical shift more than 4 ppm higher than the corresponding six-membered boronate, and concluded that **6** existed mainly as the six-membered bis(arylboronates) in solution, as its ^{11}B NMR signal was closer in chemical shift to the six-membered model boronate. Following Shinkai's example, we have identified the ring sizes of the cyclic boronates present in solutions of **1** and **2**. The ^{11}B NMR signals produced by these compounds, when dissolved in CDCl$_3$, were broad and were both centred at 30 ppm. The signal for the electronically similar tris(phenylboronate) (**5**), was also broad in CDCl$_3$ but appeared at 35 ppm. These chemical shifts are consistent with the conclusion that, analogous to their solid state forms, in solution, **1** and **2** exist predominantly as six-membered boronates, whereas the tris(phenylboronate) (**5**) exists with five-membered boronate rings. The broadness of the peaks is presumably due to fluxional behaviour of these esters in solution.

The ^{11}B NMR signal in CDCl$_3$ of the 1:2 mannitol-PBA ester,[e] likely to be similar in nature to the initial bis(phenylboronate) of D-mannitol formed in the silylation

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[d] **5** was synthesized by a similar method to that used by Kuivila et al.[17] and recrystallized from methanol.

[e] This compound was synthesized by the azeotropic removal of water from a suspension of 3/2 equiv PBA anhydride and 1 equiv D-mannitol in toluene, followed by removal of the solvent.

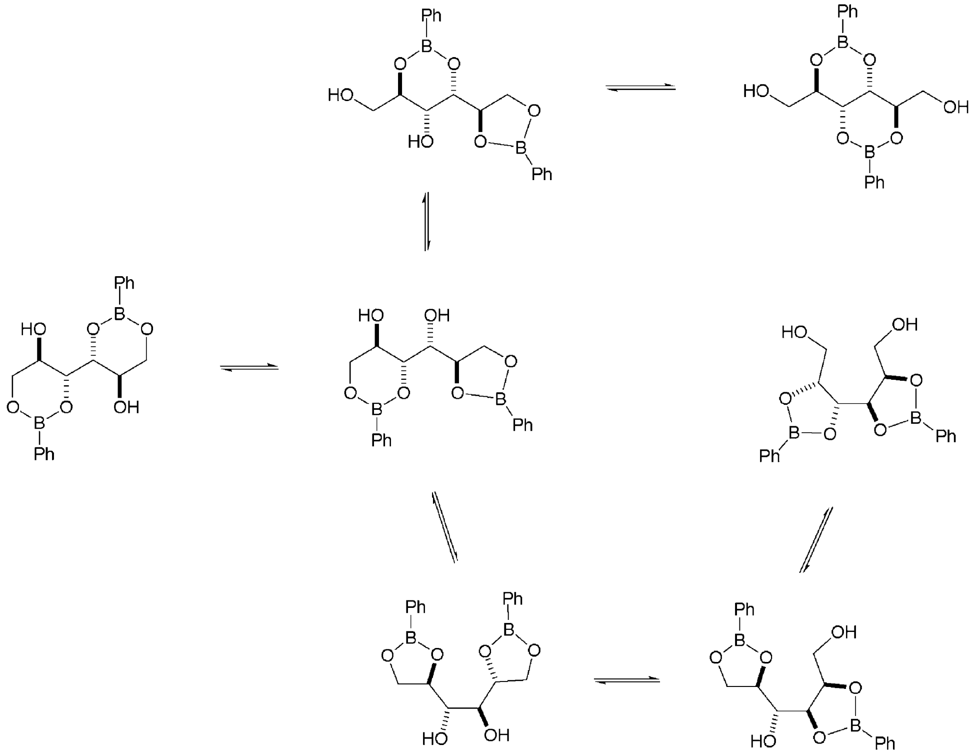

Figure 4. Possible bis(phenylboronate) esters formed with D-mannitol.

reactions, as well as in previously reported acylation and alkylation reactions,[3] was also broad and located at 33 ppm. This intermediate chemical shift suggests that, consistent with previous findings,[b] in solution, the bis(phenylboronate) of D-mannitol is in equilibrium between structures containing five- and six-membered boronate rings (Figure 4). Coordination of the free hydroxyl groups with the boron atoms in these bis(phenylboronate) esters, in which the boron atoms would tend towards a tetrahedral configuration, appears unlikely, as this would produce significantly lower ^{11}B NMR chemical shifts. In the silylation reactions of this mixture of bis(phenylboronate) esters, the disilyl ethers (**1** and **2**) result from the reaction of the silyl chlorides with the more reactive primary hydroxyl groups present in four of the transient bis(phenylboronate) D-mannitol esters shown in Figure 4. The unassisted silylation reactions of D-mannitol show some selectivity towards terminal derivitisation, but the effect of the esterification of this polyol with PBA is to further shield its secondary hydroxyl groups from attack by the silyl chloride, thus leading to enhanced 1,6-selectivity.

CONCLUSIONS

The condensation of D-mannitol with two equivalents of PBA followed by silylation with TBDMSCl and TBDPSCl produces two unusually stable bis(phenylboronates) (**1** and **2**) which were characterised in the solid state by x-ray crystallography. It was found that both esters exist as two fused six-membered rings. These findings are consistent with the structure previously determined for the threitol derivative (**6**),[11] but contrast with that of the tris(phenylboronate) ester of D-mannitol (**5**),[9] which possesses isolated five-membered cyclic boronates. The results of ^{11}B NMR experiments with **1**, **2** and **5** suggest that in $CDCl_3$ solution, these esters possess similar ring structures to those observed in the solid state, whereas the intermediate bis(phenylboronate) formed prior to silylation exists as a mixture of five- and six-membered cyclic boronates. The high stability of **1** and **2** and excellent organic solubility suggests that they may have application as novel chiral hosts for bi-dentate Lewis bases, and as chiral catalysis for a range of organic transformations.[2]

Oxidative deprotection of **1** leads to the disilylated D-mannitol (**3**) in higher yield (60% isolated yield from D-mannitol) and purity than that obtained from direct silylation of D-mannitol with TBDMSCl (~36% conversion with significant contamination from the tri-silylated product). In contrast, disilylation of D-mannitol with TBDPSCl proceeds with higher yield if PBA is omitted from the reaction mixture (~60% conversion cf 33% isolated yield of **4** from the two-step procedure) although some contamination with the tri-silylated product is still observed. Thus, the use of PBA provides the advantage of a cleaner product in the synthesis of the di-TBDPS ether of D-mannitol (**4**), and significantly improves the preparation of the corresponding diTBDMS ether (**3**), in terms of yield and product purity.

EXPERIMENTAL

General remarks and instrumentation. All non-specialized starting materials were commercially available research-grade chemicals and were used without further purification. All solvents were used as supplied except dimethyl formamide, which was dried over 4 Å molecular sieves prior to use. TLC was performed on silica coated plastic sheets (Macherey-Meigel Polygram SilG/U.V. 254). Plates were viewed using either Ultraviolet Light (254 nm) or iodine to visually develop the spots. Melting points of solid compounds were measured on a Stuart Scientific SMP3 capillary tube melting point apparatus and are uncorrected. Microanalyses were performed by Campbell Microanalytical Laboratory, University of Otago, Dunedin, New Zealand. IR spectra were recorded on a Perkin Elmer 1600 Series Fourier Transform Spectrophotometer. Samples were run as neat oils or nujol mulls on sodium chloride plates or as KBr disks.

^{1}H and ^{13}C NMR spectra were recorded on a Varian 300 MHz spectrometer using $CDCl_3$ as the solvent and tetramethylsilane (TMS) as the internal standard (δ 0.00). ^{11}B NMR spectra were recorded on a Bruker 400 MHz spectrometer using $CDCl_3$ as the solvent and $BF_3 \cdot Et_2O$ as an external standard. High-resolution mass spectra were recorded on a Bruker BioApex 47e Fourier Transform mass spectrometer. Samples were dissolved in methanol and ionized using an electrospray ionisation (ESI) source. X-Ray data were collected at 123(1) K on an Enraf–Nonius Kappa CCD single crystal diffractometer with Mo-Kα radiation (λ = 0.71073 Å). The structures were solved by direct methods with SHELXS-97 and refined by full or block matrix least-squares on

F2 using SHELXS-97 within the interface WinGX-Version 1.64.03b.[19] All non-hydrogen atoms were refined anisotropically, and C–H hydrogen positions included as invariants at geometrically estimated positions.[f]

D-Mannitol 1,6-Di-(*tert*-butyldimethylsilyl)-2:4, 3:5-O^2:O^4,O^3:O^5bis(phenylboronate) (1). Under an atmosphere of nitrogen, a solution of D-mannitol (5.0 g, 28 mmol) and phenyl boronic acid (6.8 g, 55 mmol) in DMF (300 mL) and toluene (300 mL) was heated under reflux for 2 h, with azeotropic removal of water. The toluene was then distilled from the reaction mixture and the resulting solution cooled to 0 °C. Imidazole (11.2 g, 165 mmol) was then dissolved into the stirring solution, followed by the addition of TBDMSCl (9.3 g, 62 mmol). The reaction mixture was allowed to warm to room temperature and stirred for 2 days. Following the addition of water (1250 mL), the reaction mixture was extracted with dichloromethane. The organic layers were washed with water then brine and dried over $MgSO_4$. After removal of the solvent in vacuo, the product was obtained in high purity as a viscous brown oil (15.4 g, 96%). Upon standing for several weeks, the oil crystallized to form large orange/brown prismatic crystals suitable for X-ray diffraction; mp 57–62 °C. IR (KBr disk): ν [cm^{-1}] = 2933 (C—H), 2859 (C—H), 1602 (C=C), 1444 (B—C), 1338 (B—O), 1304 (C—O), 1257 (Si—Me), 1146 (C—O), 1128, 1094 (Si—O), 838 (Si—Me), 779, 699, 647. ^{1}H NMR (300 MHz; $CDCl_3$) δ = 7.79–7.84 (m, 4H, *o*ArH), 7.36–7.43 (m, 2H, *p*ArH), 7.27–7.35 (m, 4H, *m*ArH), 4.70–4.72 (m, 2H, 3-H, 4-H), 4.37–4.43 (m, 2H, 2-H, 5-H), 3.94 (dd, $J_{1a,2}$ = 3.4 Hz, $J_{1a,1b}$ = 10.8 Hz, 2H, 1_a-H, 6_a-H), 3.88 (dd, $J_{1b,2}$ = 5.7 Hz, $J_{1b,1a}$ = 10.8 Hz, 2H, 1_b-H, 6_b-H), 0.89 (s, 18H, $SiC(CH_3)_3$), 0.09 (s, 6H, 2 × $SiCH_3$), 0.04 (s, 6H, 2 × $SiCH_3$). ^{13}C NMR (75MHz, $CDCl_3$) 134.1 (*o*C-arom.), 130.8 (*p*C-arom.), 127.5 (*m*C-arom.), 75.1 (C-2, C-5), 66.9 (C-3, C-4), 64.2 (C-1, C-6), 26.0 ($SiC(CH_3)_3$), 18.4 (SiC), −5.3 ($SiCH_3$), −5.4 ($SiCH_3$). C–B signals not observed due to broadening.

Anal. Calcd for $C_{30}H_{48}B_2O_6Si_2$: C, 61.86; H, 8.31. Found: C, 61.88; H, 8.15.

Crystal structure determination of 1: $C_{30}H_{48}B_2O_6Si_2$, Mr = 582.50, orthorhombic, space group $P\ 22_12_1$ (no. 18), a = 11.5359(**1**), b = 11.6136 (**1**), c = 25.8025 (1) Å; V = 3456.85 Å^3, Z = 4, D_x = 1.119 g/cm^3, F(000) = 1256, T = 173 K, Enraf Nonius FR590 diffractometer, graphite monochromator with CCD detector, λ(Mo-K_α) = 0.71073 Å, μ = 0.14 mm^{-1}, colourless crystal, size 0.21 × 0.17 × 0.15 mm^3, ϕ scans with ω scans to fit asymmetric unit, 35818 intensities collected $3.61< \theta<28.29°$, $-13<h<15$, $-15<k<15$, $-34<l<34$, Lp correction, no absorption correction, 8500 unique intensities (R_{int} = 0.0392). Structure solved by direct methods, full-matrix least-squares refinement based on F^2 and 361 parameters, all but H atoms refined anisotropically, H atoms refined with riding model on idealized positions. Refinement converged at R1(F) = 0.0342, ωR2(F^2, all data) = 0.0828, S = 1.0230, absolute structure parameter (Flack) −0.04(7).

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[f] Tables of atomic coordinates, bond lengths, and bond angles have been deposited with the Cambridge Crystallographic Data Centre. These tables may be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK. Reference numbers; **1**: CCDC 201656; **2**: CCDC 201657.

D-Mannitol 1,6-Di-(*tert*-butyldiphenylsilyl)-2:4, 3:5-O^2:O^4,O^3:O^5bis(phenylboronate) (2). The title compound was prepared according to the method described for the preparation of **1**, using D-mannitol (2.5 g, 14 mmol), phenylboronic acid (3.4 g, 28 mmol), DMF (150 mL), toluene (150 mL), imidazole (5.6 g, 83 mmol) and TBDPSCl (8.3 g, 30 mmol). After being allowed to warm to room temperature, the reaction mixture was stirred overnight. Following the addition of water (750 mL), the reaction mixture was extracted with dichloromethane. The organic layers were washed with water then brine and dried over $MgSO_4$. After removal of some of the solvent in vacuo, the product crystallized as a light tan solid (6.2 g, 54 %); mp 148–149 °C. Single crystals suitable for X-ray analysis were grown by slow evaporation from an acetone solution. IR (KBr disk): ν [cm^{-1}] = 2932 (C—H), 2858 (C—H), 1601 (C=C), 1472 (C=C), 1444 (B—C), 1428 (C=C), 1334 (B—O), 1303 (C—O), 1151 (C—O), 1113 (Si—O), 1022, 993, 937, 842, 822, 805, 700, 635, 611, 502. ^1H NMR (300 MHz; $CDCl_3$): δ = 7.86–7.92 (m, 4H, *o*ArH-B), 7.67–7.79 (m, 8H, *o*ArH-Si), 7.29–7.51 (m, 18H, *m*ArH-Si, *p*ArH-Si, *p*ArH-B and *m*ArH-B), 4.97 (br s, 2H, 3-H, 4-H), 4.42–4.51 (m, 2H, 2-H, 5-H), 4.06 (dd, $J_{1a,1b}$ = 4.5 Hz, $J_{1a,2}$ = 11.1 Hz, 2H, 1_a-H, 6_a-H), 3.99 (dd, $J_{1b,2}$ = 3.2 Hz, $J_{1b,1a}$ = 11.1 Hz, 2H, 1_b-H, 6_b-H), 1.06 (s, 18H, Si-$C(CH_3)_3$). ^{13}C NMR (75MHz, $CDCl_3$): δ = 135.8, 135.7 (Si-*o*C-arom.), 134.2 (B-*o*C-arom.), 133.1, 132.5 (Si-*i*C-arom.), 130.7 (B-*m*C-arom.), 130.1, 130.0 (Si-*p*C-arom.), 128.0, 127.9 (Si-*m*C-arom.), 127.6 (B-*m*C-arom.), 75.0 (C-2, C-5), 67.7 (C-3, C-4), 65.1 (C-1, C-6), 26.9 (Si-$C(CH_3)_3$), 19.3 (SiC). C–B signals not observed due to broadening.

Anal. Calcd for $C_{50}H_{56}B_2O_6Si_2$: C, 72.29; H, 6.79. Found: C, 72.55; H, 7.00.

Crystal structure determination of 2: $C_{56}H_{68}B_2O_8Si_2$, Mr = 946.94, monoclinic, space group $P12_11$ (no. 4), a = 11.8257(1), b = 12.6022 (1), c = 17.8951 (2) Å, β = 98.273 (1)°, V = 2639.15 Å^3, Z = 2, D_x = 1.192 g/cm^3, F(000) = 1012, T = 173 K, Enraf Nonius FR590 diffractometer, graphite monochromator with CCD detector, λ(Mo-K_α) = 0.71073 Å, μ = 0.12 mm^{-1}, colourless crystal, size 0.23 × 0.25 × 0.20 mm^3, ϕ scans with ω scans to fit asymmetric unit, 32361 intensities collected $3.08<\theta<28.29°$, $-15<h<15$, $-16<k<16$, $-21<l<23$, Lp correction, no absorption correction, 12958 unique intensities (R_{int} = 0.0638). Structure solved by direct methods, full-matrix least-squares refinement based on F^2 and 613 parameters, all but H atoms refined anisotropically, H atoms refined with riding model on idealized positions. Refinement converged at R1(F) = 0.0435, ωR2(F^2, all data) = 0.1018, S = 1.0440, absolute structure parameter (Flack) −0.08(6).

D-Mannitol 1,6-Di-(*tert*-butyldimethylsilyl) ether (3). A solution of **1** (0.51 g, 0.88 mmol) in ethyl acetate/acetone (1:1, 20 mL) was treated with aqueous hydrogen peroxide (30 wt%, 0.54 mL) and the mixture stirred for 4 h. Evaporation of the solvent yielded a yellow oil containing a white precipitate (0.52 g). A solution of the crude product in ethyl acetate was washed three times with NaOH (1 moldm^{-3}) then dried over $MgSO_4$. Removal of the solvent yielded a clear oil which was purified using flash column chromatography (40% EtOAc/hexane) to give the pure product as a white solid (0.12 g, 62 %); mp 58–60 °C. $[\alpha]_\nu^{20} < |1|$ (*c* 0.050, $CHCl_3$). IR (nujol): ν [cm^{-1}] = 3384 (O—H), 1255 (Si—Me), 1111 (Si—O), 1058 (C—O), 837 (Si—Me), 777. ^1H NMR (300 MHz; $CDCl_3$): δ = 3.71–3.88 (m, 8H, 1-H, 2-H, 3-H, 4-H, 5-H, 6-H), 3.31–3.38 (br d, $J_{2,OH}$ = 5.7 Hz, 2H, $CH_2CH(OH)$, no signal upon D_2O exchange), 2.88–2.94 (br d, $J_{3,OH}$ = 3.6 Hz, 2H, CH(OH)CH, no signal upon D_2O exchange), 0.90 (s, 18H, Si—C$(CH_3)_3$), 0.09 (s, 12H, Si$(CH_3)_2$). ^{13}C NMR (75MHz, $CDCl_3$): δ = 72.3 (C-2, C-5), 71.3 (C-3, C-4), 64.4 (C-1, C-6), 26.0 (Si-C$(CH_3)_3$), 18.4 (SiC), −5.2 (Si$(CH_3)_2$). MS (ESI, MeOH), *m/z*: 433.2415 (M + Na^+.$C_{18}H_{42}O_6Si_2 \cdot Na^+$ requires *m/z*, 433.2418).

Anal. Calcd for $C_{18}H_{42}O_6Si_2$: C, 52.64; H, 10.31. Found: C, 52.91; H, 10.39.

D-Mannitol 1,6-Di-(*tert*-butyldiphenylsilyl) ether (4). The diboronate ester **2** (0.61 g, 0.74 mmol) was oxidatively deprotected in an analogous way to **1**, using ethyl acetate/acetone (1:1, 20 mL) and aqueous hydrogen peroxide (30 wt%, 1.3 mL). Evaporation of the solvent yielded a yellow oil containing a white precipitate (0.82 g). A similar work-up and purification strategy (35% EtOAc/hexane) as that used for the preparation of **3** gave **4** as a viscous clear oil (0.30 g, 62 %). $[\alpha]_\nu^{20}$ = −3.3 (*c* 0.03, $CHCl_3$). IR (film): ν [cm^{-1}] = 3415 (O—H), 3071 (C—H), 2931 (C—H), 2858 (C—H), 1590 (C=C), 1472 (C=C), 1428, 1391, 1362, 1218 (C—O), 1113 (Si—O), 1007, 824, 758, 741, 702. ^{1}H NMR (300 MHz; $CDCl_3$): δ = 7.63–7.70 (m, 8H, *o*ArH), 7.34–7.48 (m, 12H, *m*ArH and *p*ArH), 3.76–3.92 (m, 8H, 1-H, 2-H, 3-H, 4-H, 5-H, 6-H), 3.06–3.14 (br s, 2H, CH_2CH(OH), no signal upon D_2O exchange), 2.80–2.88 (br s, 2H, CHCH(OH)CH, no signal upon D_2O exchange), 1.06 (s, 18H, SiC$(CH_3)_3$). ^{13}C NMR (75MHz, $CDCl_3$): δ = 135.67, 135.65 (*o*C-arom.), 132.9 (*i*C-arom.), 130.1 (*p*C-arom.), 128.0 (*m*C-arom.), 72.5 (C-2 C-5), 71.0 (C-3, C-4), 65.4 (C-1, C-6), 27.0 (SiC$(CH_3)_3$), 19.4 (SiC). MS (ESI, MeOH), *m/z*: 681.3027 (M + Na^+. $C_{38}H_{50}O_6Si_2 \cdot Na^+$ requires *m/z* 681.3044).

Anal. Calcd for $C_{38}H_{50}O_6Si_2$: C, 69.26; H, 7.65. Found: C, 69.51; H, 7.99.

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