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TETRAHEDRON: *ASYMMETRY*

A short entry to novel C(2)-methyl branched 4a-carbafuranoses

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Abstract—A concise, diastereoselective synthesis of 2-*C*-methyl-4a-carba-β-D-lyxofuranose **13** and 2-*C*-methyl-4a-carba-β-D-arabinofuranose **14**, two novel representatives of the branched-chain carbasugar family, is presented. The construction is based on the sequential execution of two strategic carbon–carbon bond-forming reactions, a vinylogous crossed aldol addition (**1**+**2**→**3**), and a rare silylative cycloaldolization (**8**→**9**+**10**).

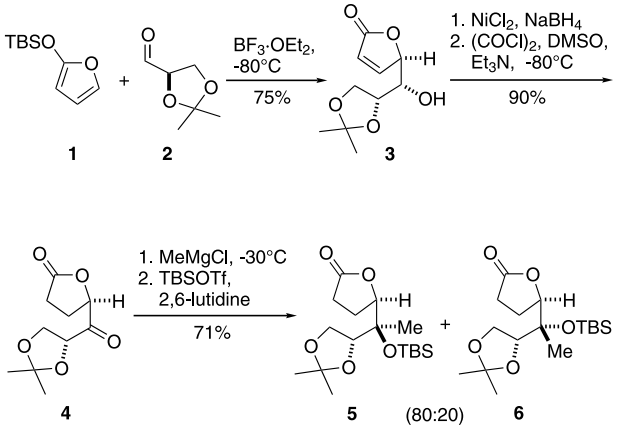
1. Introduction

Since the introduction of furan-, pyrrole-, and thiophene-based dienoxysilanes two decades ago, these carbon nucleophiles have come into widespread use.[1] Such advances have spawned an active interest in synthetic chemists and the continuing efforts to expand the scope of the heterocyclic dienoxysilane chemistry have led to practical protocols for exploiting these synthons in increasingly more challenging contexts.[2] As a further contribution in this field, the asymmetric synthesis of two novel C(2)-methyl branched 4a-carbafuranoses, **13** and **14**, is described below. Unlike the carbohydrate ensemble, where branched-chain structures constitute a widely represented compound sub-class,[3] *C*-branched carba-analogues have only been sporadically considered, and few reports have been published on this subject.[4]

2. Results and discussion

The synthesis of **13** and **14** commenced with the homochiral seven-carbon long butenolide **3**,[5] which was readily obtained through boron trifluoride-mediated vinylogous cross aldol addition[6] of 2-[(*tert*-butyldimethylsilyl)oxy]furan (Scheme 1) **1** (TBSOF) to D-glyceraldehyde acetonide **2**. Saturation of the butenolide double bond via a nickel boride procedure,[7] and standard Swern oxidation of the butanolide alcohol delivered ketone **4** in excellent yield.

Installation of the methyl substituent at C(5) was then attained by exposure of **4** to methyl magnesium chloride at −30°C, leading to two non-isolable carbinols in a 80:20 epimeric ratio (89% combined yield). Isolation of the individual components of the mixture was easily accomplished after protection of the free hydroxyls as TBS-ethers, and lactone **5**, which plausibly arises from the attack of the methyl group to the less encumbered *Si* face of the carbonyl carbon of **4**, led to the major product (57% yield from **4**).



Scheme 1.

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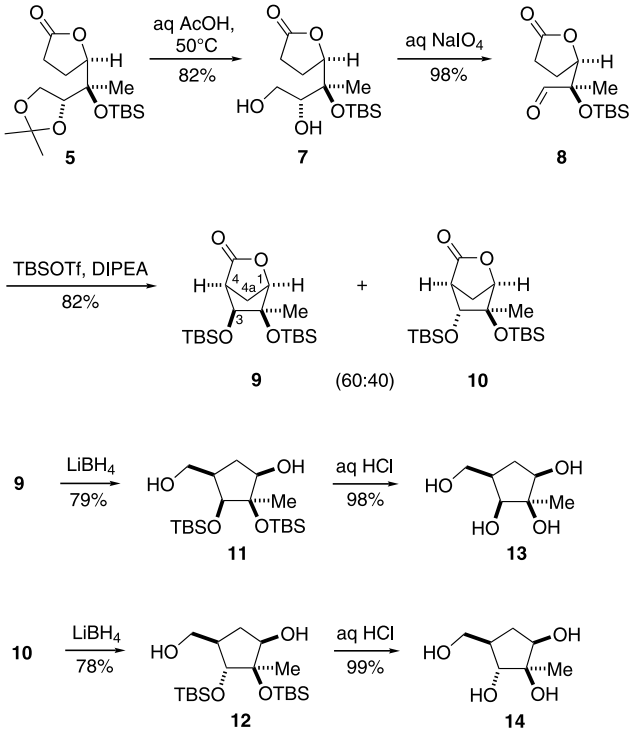
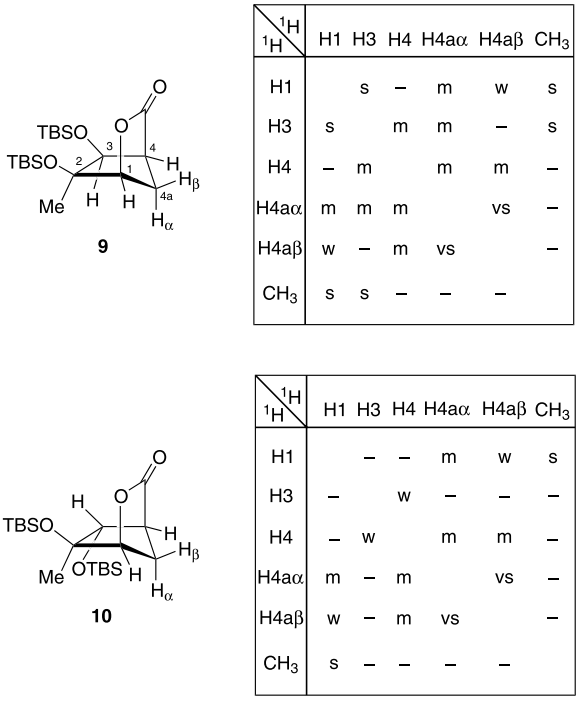
The synthesis continued (Scheme 2) with the oxidative conversion of the major isomer **5** into the requisite six-carbon aldehyde **8**, setting the stage for the key reaction in the synthesis. Thus, selective deblocking of the acetonide protection of **5** furnished diol **7**, which was shortened by one carbon atom via $NaIO_4$ treatment. The desired aldehyde **8** was formed in an 80% yield for the two steps. In the crucial transformation, slow addition of a CH_2Cl_2 solution of **8** to a preformed mixture of *tert*-butyldimethylsilyl trifluoromethanesulfonate (TBSOTf) and diisopropylethylamine (DIPEA) (3.0 mol equiv. each) in CH_2Cl_2 at ambient temperature cleanly triggered an intramolecular silylative aldolization, that resulted in the construction of the cyclopentane frame of the carbafuranose targets. In the event, isolable bicycloheptane compounds **9** and **10** formed in 49 and 33% yields, respectively.



Scheme 2.

Due to the rigid nature of their bicyclic cores, lactones **9** and **10** proved to be ideal candidates for structural elucidation. Indeed, detailed proton 2D NMR experiments allowed us to decipher definitively the molecular stereodisposition of both compounds, based on the NOE data presented in Figure 1.[8]

Completion of the synthesis required only the unmasking of the pseudoanomeric hydroxyl at C(1) (target numbering) and the hydroxymethyl group at C(4), followed by global deprotection. In parallel, exposure of **9** and **10** to $LiBH_4$ in THF resulted in reductive fission of the lactone ring of the bicycle, affording protected carbasugars **11** and **12**, which were independently liberated upon exposure to 6N HCl in THF/MeOH.



^1H / ^1H	H1	H3	H4	H4aα	H4aβ	CH_3
H1		s	–	m	w	s
H3	s		m	m	–	s
H4	–	m		m	m	–
H4aα	m	m	m		vs	–
H4aβ	w	–	m	vs		–
CH_3	s	s	–	–	–	

^1H / ^1H	H1	H3	H4	H4aα	H4aβ	CH_3
H1		–	–	m	w	s
H3	–		w	–	–	–
H4	–	w		m	m	–
H4aα	m	–	m		vs	–
H4aβ	w	–	m	vs		–
CH_3	s	–	–	–	–	

Figure 1. NOE correlations in compounds **9** and **10**. Cross peak intensities: vs, very strong; s, strong; m, medium; w, weak; –, not observed.

Novel 2-*C*-methyl-4a-carba-β-D-lyxofuranose **13** and 2-*C*-methyl-4a-carba-β-D-arabinofuranose **14** were thus synthesized via a divergent, ten-step sequence in 12 and 8% overall yields, utilizing a carbon–carbon bond construction strategy based on two key subunits, **1** and **2**, respectively, originating from furfural[9] and D-mannitol.[10]

3. Experimental

3.1. General

Flash chromatography was performed on 32–63 μm silica gel, using the indicated solvent mixtures. Analytical thin-layer chromatography was performed on silica gel 60 F_{254} plates (0.25 mm). The compounds were visualized by dipping the plates in an aqueous H_2SO_4 solution of cerium sulfate/ammonium molybdate, followed by charring with a heat gun. Proton and carbon NMR spectra were recorded with Bruker Avance 300, Varian XL-300 or Varian Mercury Plus-400 spectrometers. Chemical shifts are reported in parts per million (δ) relative to tetramethylsilane (0.0 ppm) as an internal reference, with coupling constants in hertz (Hz). Connectivity was determined by ^1H–^1H COSY experiments. ^{13}C NMR assignments were obtained from ^1H–^{13}C HETCOR experiments. Optical rotations were measured with a Perkin–Elmer 341 polarimeter at ambient temperature, using a 100 mm cell with a 1 mL capacity and specific rotations are given in units of 10^{-1} deg cm^2 g^{-1}. Elemental analyses were performed by the Microanalytical Laboratory of University of Sassari. Melting points were determined on an optical thermomicro-

scope Optiphot2-Pol Nikon. All the solvents were distilled before use: THF and Et_2O over Na/benzophenone, CH_2Cl_2 over CaH_2. 2-[(*tert*-Butyldimethylsilyl)-oxy]furan **1** (TBSOF) was obtained from 2-furaldehyde (Aldrich) following a reported method.[9] 2,3-*O*-Isopropylidene-D-glyceraldehyde **2** was prepared from D-mannitol according to a literature protocol.[10]

3.2. (1′*S*,4″*R*,5*R*)-5-[(2,2-Dimethyl-1,3-dioxolan-4-yl)-hydroxymethyl]-5*H*-furan-2-one, 3

The title compound was prepared from (silyloxy)furan **1** (2.50 g, 12.60 mmol) and glyceraldehyde **2** (1.97 g, 15.14 mmol) according to a previously described procedure.[5] Butenolide **3** (2.03 g) was isolated in 75% yield as white crystals: mp 125°C; $[\alpha]_D^{20}$ +69.6 (*c* 1.0, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 7.59 (dd, $J=5.8$, 1.7 Hz, 1H), 6.17 (dd, $J=5.8$, 1.9 Hz, 1H), 5.27 (dt, $J=3.8$, 1.8 Hz, 1H), 4.18 (m, 2H), 4.05 (m, 1H), 3.67 (td, $J=7.2$, 4.0 Hz, 1H), 2.94 (d, $J=6.6$ Hz, 1H), 1.42 (s, 3H), 1.37 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 176.4, 154.3, 122.1, 109.8, 84.2, 75.5, 72.9, 67.1, 26.7, 25.1. Anal. calcd for $C_{10}H_{14}O_5$: C, 56.07; H, 6.59. Found: C, 55.91; H, 6.73.

3.3. (4′*R*,5*R*)-5-(2,2-Dimethyl-1,3-dioxolan-4-carbonyl)-dihydrofuran-2-one, 4

A solution of **3** (2.03 g, 9.48 mmol) in 80 mL of absolute MeOH was cooled to 0°C and treated with 563 mg (2.37 mmol) of $NiCl_2{\cdot}6H_2O$. The resulting mixture was stirred at the same temperature for 15 min before the addition of 179 mg (4.74 mmol) of $NaBH_4$. After 30 min, a further portion of $NaBH_4$ (90 mg, 2.37 mmol) was added, and the reaction was allowed to stir for an additional 10 min. The reaction was then quenched with saturated NH_4Cl solution and extracted with CH_2Cl_2 (3×50 mL). The combined extracts were dried ($MgSO_4$) and concentrated under vacuum. Flash chromatographic purification (hexanes/EtOAc, 40:60) afforded a lactone intermediate (2.05 g, 100%) as a colorless oil: $[\alpha]_D^{20}$ −13.9 (*c* 0.9, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 4.77 (td, $J=7.5$, 2.1 Hz, 1H), 4.14 (m, 2H), 4.01 (m, 1H), 3.53 (dd, $J=6.0$, 2.3 Hz, 1H), 3.35 (d, $J=7.4$ Hz, 1H), 2.64 (ddd, $J=17.7$, 8.5, 7.2 Hz, 1H), 2.51 (ddd, $J=17.7$, 9.7, 7.6 Hz, 1H), 2.31 (m, 2H), 1.41 (s, 3H), 1.35 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.0, 109.3, 79.9, 75.6, 73.7, 66.8, 28.5, 26.6, 25.1, 23.6. Anal. calcd for $C_{10}H_{16}O_5$: C, 55.55; H, 7.46. Found: C, 55.33; H, 7.60.

To a solution of oxalyl chloride (2.42 mL, 27.75 mmol) in CH_2Cl_2 (140 mL) at −80°C, under argon was added dropwise a solution of DMSO (2.63 mL, 37.0 mmol) in CH_2Cl_2 (16 mL). After 30 min, a solution of lactone intermediate (2.0 g, 9.25 mmol) in CH_2Cl_2 (18 mL) was added dropwise. After 30 min at −80°C, Et_3N (12.89 mL, 92.5 mmol) was added. The reaction mixture was stirred at −80°C for 30 min and then warmed slowly to 0°C during 1 h. After 30 min at 0°C toluene (400 mL) was added, the resulting mixture was filtered through a Celite pad and the filtrates were concentrated in vacuo. The residue was dissolved in hexanes (400 mL), filtered again, and concentrated under reduced pressure to give crude ketone **4** (1.78 g, 90%) as a glassy solid: $[\alpha]_D^{20}$ +2.6 (*c* 1.9, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 5.35 (dd, $J=8.4$, 5.1 Hz, 1H), 4.74 (dd, $J=8.1$, 5.4 Hz, 1H), 4.29 (t, $J=8.4$ Hz, 1H), 4.07 (dd, $J=9.0$, 5.4 Hz, 1H), 2.54 (m, 3H), 2.30 (m, 1H), 1.43 (s, 3H), 1.38 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.9, 176.0, 111.1, 79.1, 78.5, 66.3, 26.5, 25.7, 24.3, 24.1. Anal. calcd for $C_{10}H_{14}O_5$: C, 56.07; H, 6.59. Found: 56.21; H, 6.72.

3.4. (1′*R*,4″*R*,5*R*)-5-[1-(*tert*-Butyldimethylsilanyl)-1-(2,2-dimethyl-1,3-dioxolan-4-yl)hydroxyethyl]dihydrofuran-2-one, 5 and (1′*S*,4″*R*,5*R*)-5-[1-(*tert*-butyldimethylsilanyl)-1-(2,2-dimethyl-1,3-dioxolan-4-yl)hydroxyethyl]dihydrofuran-2-one, 6

To a solution of ketone **4** (1.75 g, 8.17 mmol) in anhydrous THF (80 mL), under argon at −30°C were slowly added 2.72 mL (8.17 mmol) of MeMgCl (3 M in THF). The mixture was stirred at −30°C for 4 h, and then it was quenched by addition of saturated NH_4Cl solution. The separated aqueous layer was extracted with CH_2Cl_2 (3×10 mL) and the combined organic extracts were dried, filtered and concentrated under vacuum to leave a residue that was purified by flash chromatography (hexanes/EtOAc, 30:70). The inseparable mixture of carbinol intermediates (1.67 g, 89%; 80:20 ratio by NMR) was used without further purification in the next protection reaction. *tert*-Butyldimethylsilyl trifluoromethanesulfonate (TBSOTf) (1.81 mL, 7.88 mmol) and 2,6-lutidine (2.75 mL, 23.63 mmol) were sequentially added to a stirred solution of the mixture of carbinols (1.65 g, 7.16 mmol) in anhydrous CH_2Cl_2 (18 mL) under argon atmosphere at room temperature. After 6 h the reaction was quenched by addition of saturated NH_4Cl solution and the mixture was extracted with CH_2Cl_2 (3×20 mL). The combined organic layer was dried ($MgSO_4$), filtered and concentrated to give a crude residue that was purified by flash chromatography (hexanes/EtOAc, 85:15) furnishing protected lactones **5** (1.58 g, 64%) and **6** (395 mg, 16%) as colorless oils:

Compound 5: $[\alpha]_D^{20}$ −5.0 (*c* 2.2, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 4.05 (m, 4H), 2.66 (dt, $J=18.3$, 6.9 Hz, 1H), 2.51 (dt, $J=18.3$, 7.2 Hz, 1H), 2.19 (dtd, $J=13.8$, 6.9, 3.9 Hz, 1H), 1.85 (dq, $J=13.8$, 7.0 Hz, 1H), 1.37 (s, 3H), 1.36 (s, 3H), 1.21 (s, 3H), 0.90 (s, 9H), 0.11, (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5, 110.0, 83.4, 78.0, 67.7, 64.4, 26.8, 26.3, 25.9, 25.6 (3C), 25.2, 18.5, 17.9, −4.5, −5.2. Anal. calcd for $C_{17}H_{32}O_5Si$: C, 59.27; H, 9.36. Found: C, 59.23; H, 9.31.

Compound 6: $[\alpha]_D^{20}$ +17.5 (*c* 0.8, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 4.52 (dd, $J=6.6$, 5.4 Hz, 1H), 4.08 (m, 2H), 3.93 (dd, $J=3.6$, 2.1 Hz, 1H), 2.73 (ddd, $J=18.6$, 12.0, 8.1 Hz, 1H), 2.47 (ddd, $J=18.6$, 6.9, 1.5 Hz, 1H), 2.14 (dddd, $J=14.4$, 12.0, 6.9, 2.1 Hz, 1H), 1.89 (dddd, $J=14.4$, 7.8, 3.9, 1.5 Hz, 1H), 1.43 (s, 3H), 1.31 (s, 3H), 1.28 (s, 3H), 0.91 (s, 9H), 0.14 (s, 3H), 0.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 109.3, 85.9, 74.2,

66.6, 65.0, 26.3, 25.8 (3C), 24.6, 24.4, 24.2, 19.0, 18.2, −4.6, −5.0. Anal. calcd for $C_{17}H_{32}O_5Si$: C, 59.27; H, 9.36. Found: C, 59.11; H, 9.51.

3.5. (2′*R*,3′*R*,5*R*)-5-[2-(*tert*-Butyldimethylsilanyloxy)-3,4-dihydroxybutyl]dihydrofuran-2-one, 7

Protected lactone **5** (1.55 g, 4.50 mmol) was dissolved in 16 mL of 80% aqueous acetic acid, and the resulting solution was allowed to stir at 50°C. The reaction was monitored by TLC and was judged complete after 12 h. The solution was diluted with H_2O and extracted with EtOAc (3×15 mL). The combined organic extracts were washed with saturated $NaHCO_3$ solution, dried ($MgSO_4$), filtered and concentrated under vacuum to leave a crude residue that was flash chromatographed (EtOAc/hexanes, 80:20). A pure terminal diol **7** was obtained (1.12 g, 82%) as a colorless oil: $[\alpha]_D^{20}$ −12.5 (*c* 2.4, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.31 (dd, J=9.6, 4.8 Hz, 1H), 3.90 (dd, J=11.2, 6.0 Hz, 1H), 3.78 (m, 1H), 3.64 (td, J=6.8, 3.6 Hz, 1H), 2.70 (bs, 1H), 2.67 (ddd, J=18.0, 6.8 4.4 Hz, 1H), 2.54 (ddd, J=18.0, 9.6, 7.6 Hz, 1H), 2.14 (bs, 1H), 1.9–2.0 (m, 2H), 1.31 (s, 3H), 0.89 (s, 9H), 0.13 (s, 3H), 0.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 87.8, 72.5, 65.9, 62.0, 27.6, 25.8 (3C), 25.0, 18.0, 17.7, −4.1, −4.9. Anal. calcd for $C_{14}H_{28}O_5Si$: C, 55.23; H, 9.27. Found: C, 55.09; H, 9.39.

3.6. (2*R*,2′*R*)-2-(*tert*-Butyldimethylsilanyloxy)-2-(5-oxotetrahydrofuran-2-yl)propionaldehyde, 8

The diol **7** (1.10 g, 3.61 mmol) was dissolved in CH_2Cl_2 (75 mL) and treated with a 0.65 M aqueous $NaIO_4$ solution (7.3 mL) and chromatography grade SiO_2 (7.8 g). The resulting heterogeneous mixture was vigorously stirred at room temperature until complete consumption of the starting material (6 h, monitoring by TLC). The slurry was filtered under suction and the silica thoroughly washed with CH_2Cl_2 and EtOAc. The filtrates were evaporated to afford aldehyde **8** (964 mg, 98%) as a glassy solid: $[\alpha]_D^{20}$ −52.9 (*c* 2.1, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.60 (s, 1H), 4.06 (dd, J=4.0, 2.0 Hz, 1H), 2.70 (ddd, J=18.4, 12.0, 6.8 Hz, 1H), 2.44 (ddd, J=18.4, 6.4, 2.4 Hz, 1H), 1.86 (dddd, J=14.4, 7.2, 4.4, 2.8 Hz, 1H), 1.72 (dddd, J=14.4, 12.0, 6.0, 2.0 Hz, 1H), 1.37 (s, 3H), 0.86 (s, 9H), 0.08 (s, 3H), 0.07 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.9, 168.8, 90.4, 65.1, 25.9, 25.7 (3C), 24.5, 19.5, 18.0, −4.5, −4.9. Anal. calcd for $C_{13}H_{24}O_4Si$: C, 57.32; H, 8.88. Found: C, 57.45; H, 8.74.

3.7. (1*R*,4*S*,5*S*,6*R*)-5,6-Bis-(*tert*-butyldimethylsilanyloxy)-6-methyl-2-oxabicyclo[2.2.1]heptan-3-one, 9 and (1*R*,4*S*,5*R*,6*R*)-5,6-bis-(*tert*-butyldimethylsilanyloxy)-6-methyl-2-oxabicyclo[2.2.1]heptan-3-one, 10

To a solution of diisopropylethylamine (DIPEA) (1.84 mL, 10.59 mmol) in anhydrous CH_2Cl_2 (40 mL) at 25°C, under an argon atmosphere, was added TBSOTf (2.43 mL, 10.59 mmol) and the resulting mixture was stirred at the same temperature for 10 min before aldehyde **10** (962 mg, 3.53 mmol) dissolved in anhydrous CH_2Cl_2 (20 mL) was added. The reaction was monitored by TLC and was judged complete after 12 h. The solution was then quenched with saturated NH_4Cl solution, and extracted with CH_2Cl_2 (3×20 mL). The combined extracts were dried ($MgSO_4$) and concentrated under reduced pressure. The oily residue was purified by flash chromatography (hexanes/EtOAc, 93:7) to give 669 mg (49%) of **9** accompanied by 450 mg (33%) of **10**.

Compound 9: a colorless oil; $[\alpha]_D^{20}$ +18.6 (*c* 2.8, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.09 (dd, J=8.9, 3.5 Hz, 1H), 3.80 (d, J=1.2 Hz, 1H), 2.71 (dd, J=4.4, 1.5 Hz, 1H), 2.30 (ddd, J=13.5, 8.9, 4.5 Hz, 1H), 1.51 (dd, J=13.6, 3.5 Hz, 1H), 1.38 (s, 3H), 0.90 (s, 18H) 0.09 (s, 9 H), 0.07 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 177.0, 91.8, 78.7, 72.1, 50.7, 32.8, 25.7 (3C), 25.6 (3C), 18.1, 18.0, 13.3, −4.6, −4.7, −4.9, −5.0. Anal. calcd for $C_{19}H_{38}O_4Si_2$: C, 59.02; H, 9.91. Found: C, 58.85; H, 10.16.

Compound 10: a colorless oil; $[\alpha]_D^{20}$ −8.8 (*c* 1.4, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.33 (dd, J=8.4, 2.8 Hz, 1H), 3.95 (bs, 1H), 2.63 (dd, J=4.4, 1.2 Hz, 1H), 2.52 (ddd, J=12.8, 8.4, 4.5 Hz, 1H), 1.55 (bd, J=12.8 Hz, 1H), 1.38 (s, 3H), 0.89 (s, 18H), 0.09 (s, 3H), 0.08 (s, 3H), 0.07 (s, 3H), 0.06 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.9, 90.4, 79.6, 73.7, 48.2, 33.3, 25.8 (3C), 25.6 (3C), 18.2, 17.9, 13.2, −4.3, −4.5, −4.7, −5.0. Anal. calcd for $C_{19}H_{38}O_4Si_2$: C, 59.02; H, 9.91. Found: 59.17; H, 10.17.

3.8. (1*R*,2*R*,3*S*,4*R*)-2,3-Di-*O*-(*tert*-butyldimethylsilanyl)-4-hydroxymethyl-2-methylcyclopentane-1,2,3-triol, 11

A solution of bicyclic adduct **9** (667 g, 1.72 mmol) in anhydrous THF (9 mL), under an argon atmosphere, was cooled to 0°C and treated dropwise with $LiBH_4$ (860 μL of 2.0 M solution in THF, 1.72 mmol). After 15 min the ice bath was removed and the temperature was allowed to reach 25°C, while further portions of $LiBH_4$ (4×860 μL, 4×1.72 mmol) were added over 6 h. The reaction mixture was then quenched with saturated NH_4Cl solution and 5% aqueous citric acid. The separated aqueous layer was extracted with CH_2Cl_2 (2×10 mL) and EtOAc (10 mL). The combined organic solutions were dried, filtered and concentrated to leave a residue which was purified by flash chromatography (hexanes/EtOAc, 90:10) to give partially protected carbasugar **11** (531 mg, 79%) as an oil: $[\alpha]_D^{20}$ −15.4 (*c* 0.7, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.74 (ddd, J=11.2, 9.2, 2.8 Hz, 1H), 3.68 (dd, J=9.2, 6.0 Hz, 1H), 3.54 (td, J=10.4, 4.8 Hz, 1H), 3.14 (d, J=10.0 Hz, 1H), 2.91 (dd, J=9.2, 2.8 Hz, 1H), 2.31 (quintd, J=9.2, 4.8 Hz, 1H), 1.84 (ddd, J=12.4, 8.8, 6.0 Hz, 1H), 1.63 (bs, 1H), 1.39 (dt, J=12.4, 9.2 Hz, 1H), 1.26 (s, 3H), 0.92 (s, 9H), 0.91 (s, 9H), 0.20 (s, 3H), 0.18 (s, 3H), 0.10 (s, 3H), 0.08 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 82.2, 77.8, 77.7, 64.3, 40.0, 33.6, 26.3 (3C), 26.2 (3C), 23.2, 18.7 (2C), −2.0, −2.1, −4.1, −4.5. Anal. calcd for $C_{19}H_{42}O_4Si_2$: C, 58.41; H, 10.84. Found: C, 58.27; H, 10.93.

3.9. (1*R*,2*R*,3*S*,4*R*)-4-Hydroxymethyl-2-methylcyclopentane-1,2,3-triol [2-*C*-methyl-4a-carba-β-D-lyxofuranose], 13

Compound **11** (530 mg, 1.36 mmol) was treated with 13 mL of 6N HCl/THF/MeOH (1:2:2) solution at room temperature. The reaction was stirred for 4 h and then concentrated to dryness under vacuum. The oily crude residue was flash chromatographed (EtOAc/MeOH, 80:20) to afford fully deprotected carbasugar **13** (216 mg, 98%) as a glassy solid: $[\alpha]_D^{20}$ −3.1 (*c* 0.3, H_2O); ^1H NMR (400 MHz, D_2O) δ 3.82 (d, $J=7.2$ Hz, 1H, H3), 3.72 (t, $J=7.6$ Hz, 1H, H1), 3.67 (dd, $J=10.8$, 6.4 Hz, 1H, H5), 3.58 (dd, $J=10.8$, 6.0 Hz, 1H, H5′), 2.23 (tq, $J=8.8$, 6.4 Hz, 1H, H4), 2.12 (ddd, $J=13.2$, 8.8, 7.2 Hz, 1H, H4a), 1.41 (dt, $J=13.2$, 8.4 Hz, 1H, H4a′), 1.16 (s, 3H, Me); ^{13}C NMR (100 MHz, D_2O) δ 77.6 (C2), 76.6 (C1 or C3), 75.2 (C1 or C3), 61.7 (C5), 39.5 (C4), 32.8 (C4a), 22.0 (Me). Anal. calcd for $C_7H_{14}O_4$: C, 51.84; H, 8.70. Found: 51.97; H, 8.54.

3.10. (1*R*,2*R*,3*R*,4*R*)-2,3-Di-*O*-(*tert*-butyldimethylsilanyl)-4-hydroxymethyl-2-methylcyclopentane-1,2,3-triol, 12

The title compound was prepared from bicyclic adduct **10** (440 mg, 1.14 mmol) according to the procedure described for compound **11**. After purification by flash chromatography (hexanes/EtOAc, 80:20) partially protected methyl carbasugar **12** (346 mg, 78%) was recovered as a colorless oil: $[\alpha]_D^{20}$ −17.5 (*c* 0.8, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 3.89 (t, $J=7.2$ Hz, 1H), 3.70 (dd, $J=10.4$, 4.8 Hz, 1H), 3.68 (d, $J=3.6$ Hz, 1H), 3.62 (dd, $J=10.4$, 4.4 Hz, 1H), 2.76 (bs, 1H), 2.53 (bs, 1H), 2.10 (ddd, $J=12.8$, 9.2, 7.2 Hz, 1H), 1.97 (tq, $J=9.2$, 4.6 Hz, 1H), 1.52 (dt, $J=12.8$, 7.6 Hz, 1H), 1.14 (s, 3H), 0.91 (s, 9H), 0.89 (s, 9H), 0.10 (s, 6H), 0.09 (s, 3H), 0.07 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 80.5, 80.0, 78.9, 64.6, 46.6, 32.5, 25.9 (6C), 20.6, 18.2, 18.1, −4.2, −4.3, −4.4, −4.8. Anal. calcd for $C_{19}H_{42}O_4Si_2$: C, 58.41; H, 10.84. Found: C, 58.57; H, 10.68.

3.11. (1*R*,2*R*,3*R*,4*R*)-4-Hydroxymethyl-2-methylcyclopentane-1,2,3-triol [2-*C*-methyl-4a-carba-β-D-arabinofuranose], 14

The title compound was prepared from carbasugar **12** (345 mg, 0.88 mmol) according to the procedure described for compound **13**. After flash chromatographic purification (EtOAc/MeOH, 80:20) fully deprotected methyl carbasugar **14** (142 mg, 99%) was recovered as a glassy solid: $[\alpha]_D^{20}$ +10.0 (*c* 0.1, H_2O); ^1H NMR (400 MHz, D_2O) δ 3.72 (t, $J=6.8$ Hz, 1H, H1), 3.65 (dd, $J=10.8$, 5.6 Hz, 1H, H5), 3.5–.6 (m, 2H, H3, H5′), 2.14 (dt, $J=14.0$, 7.2 Hz, 1H, H4a), 1.83 (m, 1H, H4), 1.30 (dt, $J=14.4$, 8.0 Hz, 1H, H4a′), 1.14 (s, 3H, Me); ^{13}C NMR (100 MHz, D_2O) δ 79.7 (C2), 79.1 (C1 or C3), 75.4 (C1 or C3), 61.6 (C5), 43.2 (C4), 31.5 (C4a), 18.8 (Me). Anal. calcd for $C_7H_{14}O_4$: C, 51.84; H, 8.70. Found: C, 51.98; H, 8.54.

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