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An efficient conversion of D-mannitol into D-fructose and 1,5-dideoxy-1,5-imino-D-mannitol (1-deoxymannojirimycin)

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ABSTRACT

The utility of bis(tributyltin)oxide–bromine for the selective oxidation of secondary hydroxyl groups in the presence of primary hydroxyl groups has been further demonstrated by the efficient conversions of D-mannitol into D-fructose and 1,5-dideoxy-1,5-imino-D-mannitol (1-deoxymannojirimycin).

INTRODUCTION

Oxidation by the distannoxane $[(R_3Sn)_2O]$–bromine system is an effective method for the conversion of secondary alcohols to ketones in the presence of primary alcohols[1]. A more recent observation is that, in the cases of molecules containing two secondary hydroxyl groups, it is possible, using this system, to oxidize one selectively[2]. In this article we describe the utilization of the regio-differentiating properties of distannoxane–bromine for the efficient syntheses of D-fructose (**8**) and 1,5-dideoxy-1,5-imino-D-mannitol (1-deoxymannojirimycin) (**11**) from D-mannitol. The pivotal step in the synthesis of **8** involved the oxidation of 3,4-di-*O*-benzyl-D-mannitol (**4**) to give 3,4-di-*O*-benzyl-D-fructose (**7**), isolated in both the furanose and pyranose forms. Similarly, oxidation of 6-azido-3,4-di-*O*-benzyl-6-deoxy-D-mannitol (**9**) gave 6-azido-3,4-di-*O*-benzyl-6-deoxy-D-fructofuranose (see **10**). By hydrogenolysis over palladium-on-charcoal under acidic conditions, compounds **7** and **10** were easily transformed into D-fructose (**8**) and 1-deoxymannojirimycin (**11**), respectively.

RESULTS AND DISCUSSION

1,2:5,6-Di-*O*-isopropylidene-D-mannitol (**2**) was prepared from D-mannitol (**1**) by known procedures, namely, that involving the use of 2-methoxypropene at 0°C[3],

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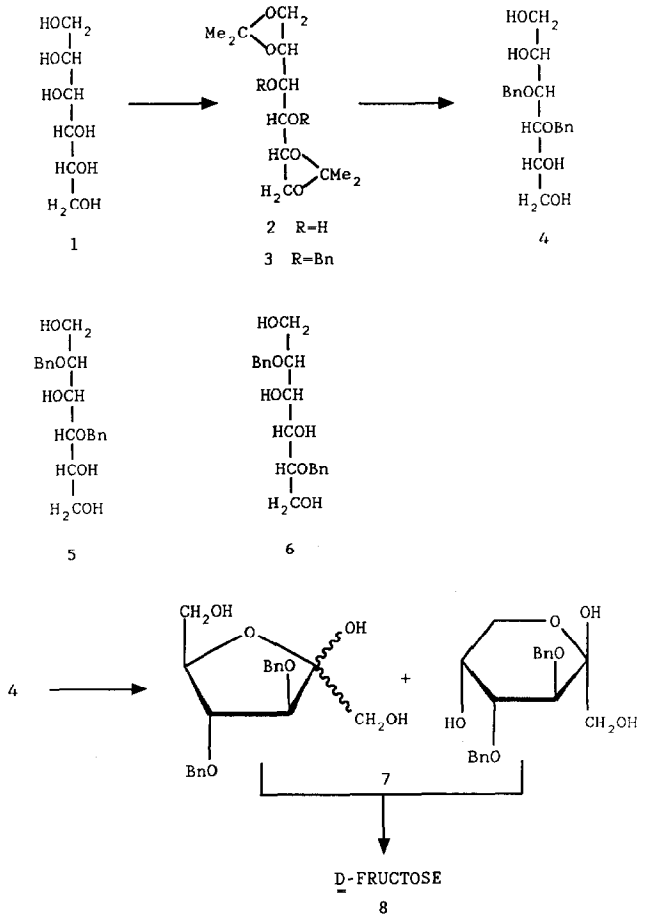


Scheme 1.

or that involving the use of acetone in the presence of zinc chloride[4]. Using the former procedure[3], we obtained a mixture of **2** and of two isomers, which was difficult to resolve. However, after benzylation and *O*-deisopropylidenation of the mixture, the desired compound **4** (ref. 5) was isolated by silica gel chromatography, together with 2,4-di-*O*-benzyl-D-mannitol (**5**) and 2,5-di-*O*-benzyl-D-mannitol (**6**) (refs. 6 and 7). In contrast, the more recent procedure[4], which employs acetone–zinc chloride, provided **2** predominantly. The structural assignment for **5** was corroborated by its ^{13}C NMR spectrum and by tritylation using trityl chloride–pyridine.

In Table I are summarized the ^{13}C NMR data of compounds **4**, **5**, and **6**. The chemical shifts of C-5 and C-6 in the spectra of both **4** and **5** are respectively similar because of the structural similarity in the C-4–C-5–C-6 region. The signal (δ 77.14) of C-4 in the spectrum of **5** is shifted downfield relative to the

TABLE I

Partial ^{13}C NMR spectral data of compounds **4**, **5**, and **6**

Compound	Chemical shifts (δ)					
	C-1	C-2	C-3	C-4	C-5	C-6
4 [a]	63.50	71.64	73.90	73.90	71.64	63.50
5 [b]	59.96	78.46	69.88	77.14	71.80	63.48
6 [b]	61.08	79.70	69.77	69.77	79.70	61.08

[a] For a solution on $CDCl_3$. [b] For a solution in $CDCl_3$–MeOH. The chemical shifts (δ) are given in ppm downfield from the signal of Me_4Si (external standard).

corresponding signal (δ 73.90) in the spectrum of **4** because of the lack of the benzyl group at C-3 in the case of **5**. Consistent with this downfield shift of the C-4 signal is the upfield shift of the C-3 signal (δ 69.88) in the spectrum of **5** relative to the corresponding signal (δ 73.90) in the spectrum of **4**. Also, consistent with the structural similarity in the C-1–C-2–C-3 region of **5** and **6** is the observation of similar chemical shifts for the C-1, C-2, and C-3 signals in the spectra of these compounds.

Based on its ^{13}C NMR data, compound **5** should have two primary hydroxyl groups, a structural feature which was confirmed by the formation of a di-*O*-trityl derivative. These data are consistent with the structure of compound **5** being that of 2,4-di-*O*-benzyl-D-mannitol. The other possible unsymmetrical di-*O*-benzyl derivative, namely 2,3-di-*O*-benzyl-D-mannitol, would have to have been derived from 1,4:5,6-di-*O*-isopropylidene-D-mannitol in which a very unfavorable, seven-membered, acetal-ring system would be required.

Benzylation of **2** with benzyl chloride–potassium hydroxide in dimethyl sulfoxide gave 3,4-di-*O*-benzyl-1,2:5,6-di-*O*-isopropylidene-D-mannitol (**3**)[5,8] in 70% yield. Removal of the *O*-isopropylidene groups by treatment with 60% aqueous acetic acid afforded 3,4-di-*O*-benzyl-D-mannitol (**4**) in 84% yield. The oxidation of **4** using bis(tributyltin)oxide–bromine (2.3 equiv) gave 3,4-di-*O*-benzyl-D-fructose (**7**) in 85% yield. This compound was present in the α-furanose (**7αf**), β-furanose (**7βf**), and β-pyranose (**7βp**) forms. The ratio of these tautomers was 1:3:2, respectively, based on the peak heights of the signals of the anomeric carbons (C-2) in the ^{13}C NMR spectrum[9]. The presence of the α-fructopyranose tautomer was not detected.

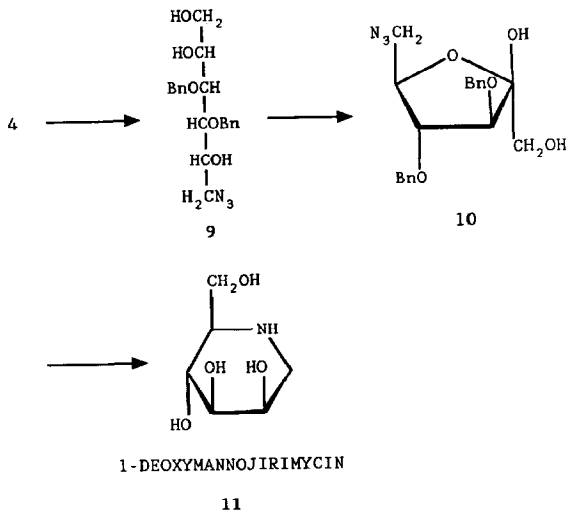
Hydrogenolysis of **7** (as a mixture of isomers) over palladium-on-charcoal in slightly acidic methanol gave D-fructose (**8**) in quantitative yield, which was identified by ^{13}C NMR spectral data, melting point, and specific rotation[10].

Interestingly, the secondary hydroxyl group in **7βp** was not oxidized, even when 4.5 equiv of the tin reagent were used. Thus, to explore further the steric requirements for this type of reagent, we examined the oxidation of several other protected monosaccharides. It has been reported[2] already that treatment of 1,2-*O*-isopropylidene-α-D-glucofuranose under similar conditions led to oxidation

at C-5. We have found that the reaction with 1,2-*O*-isopropylidene-β-D-fructopyranose afforded more than two oxidation products; however, 1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose[11] and 1,2 : 4,5-di-*O*-isopropylidene-β-D-fructopyranose[10] were unreactive to the oxidizing reagent. Clearly, in addition to the pronounced discrimination of this reagent between secondary and primary alcohols, it is also quite sensitive to the steric environment around the secondary alcohol. However, the exact mechanistic details are still unknown.

To further illustrate the high selectivity of this reagent and to demonstrate its utility in asymmetric synthesis, the reagent was employed for the efficient synthesis of the important azasugar derivative, 1,5-dideoxy-1,5-imino-D-mannitol (**11**), from D-mannitol. Compound **11** is a glycosidase inhibitor[12], and several syntheses, both chemical and enzymatic, have been reported[13–26]. The method described here compares favorably in terms of simplicity and efficiency to these syntheses.

As a consequence of the C_2 symmetry of **4**, the compound was converted into 3,4-di-*O*-benzyl-6-*O*-*p*-tolylsulfonyl-D-mannitol by treatment with 1 equiv of *p*-toluenesulfonyl chloride in pyridine. The subsequent S_N2 displacement of the tosylate with azide ion was accomplished in 10:1 *N*,*N*-dimethylformamide–water at 100°C to afford 6-azido-3,4-di-*O*-benzyl-6-deoxy-D-mannitol (**9**) in 51% yield (overall yield from **4**), together with unreacted starting material **4**, which was recycled to increase the yield to 64% based on consumed starting material. Compound **9** was isolated in a form solvated with ethyl acetate, as indicated by both NMR measurement and elemental analysis. An oxidation procedure similar to that described for the conversion of **4** into **7** was used to convert **9** into 6-azido-3,4-di-*O*-benzyl-6-deoxy-D-fructofuranose in both the α- and β-forms in 75% yield. Crystallization from ethyl acetate–hexane gave the β-form (**10**).



Scheme 2.

Hydrogenolysis of **10** over palladium-on-charcoal in methanol did not give the expected product; instead a brown syrup consisting of many compounds was obtained. However, hydrogenolysis of **10** in 3 : 1 methanol–water containing 0.1 N HCl afforded 1-deoxymannojirimycin (**11**) in 87% yield. Thus, the hydrogenolytic removal of benzyl groups, reduction of the azido group, and subsequent formation and reduction of the Schiff-base were accomplished without isolation of any intermediates. It is noteworthy that the process required an excess of hydrochloric acid for efficient debenzylation. The synthetic sample of **11** had NMR spectral data, melting point, and specific rotation in agreement with values reported in the literature[15–18,20,27].

EXPERIMENTAL

General methods.—Melting points were determined on a Fisher–Johns apparatus and are uncorrected. Optical rotations were measured with a Perkin–Elmer model 241 polarimeter for solutions in a 0.1- or 1.0-dm cell at room temperature. Nuclear magnetic resonance (NMR) spectra were recorded with a Bruker AC-F200 spectrometer, at 200.132 MHz for the ^{1}H NMR spectra and at 50.323 MHz for the ^{13}C NMR spectra. Chemical shifts (δ) are given in ppm downfield from the signal of Me_4Si (external reference). When deuterium oxide was the solvent, the signal of HOD at 4.75 was used as a standard. Mass spectra were recorded on a VG Analytical ZAB-E mass spectrometer. Infrared (IR) spectra were recorded with a Perkin–Elmer 598 spectrophotometer. Thin-layer chromatography (TLC) was performed using glass plates precoated with E. Merck Silica Gel 60F-254 as the adsorbent (layer thickness, 0.25 mm). The developed plates were air-dried and sprayed with a solution of cerium(IV) sulfate (1%) and molybdic acid (1.5%) in 10% aq H_2SO_4, and heated at 150°C. Column chromatography was performed on E. Merck no. 9385-5 Silica Gel-50 (230–400 mesh). Solvents were evaporated under reduced pressure at < 40°C.

3,4-Di-O-benzyl-1,2 : 5,6-di-O-isopropylidene-D-mannitol (**3**).—To a solution of 1,2 : 5,6-di-*O*-isopropylidene-D-mannitol (**2**; 8.0 g, 30.5 mmol) in dry Me_2SO (100 mL) were added powdered KOH (8.0 g) and benzyl chloride (15 mL). The mixture was stirred at room temperature for 4 h. Ice-cold water (200 mL) was added and the aq solution was extracted with $CHCl_3$ (2 × 150 mL); the organic solution was washed twice with water and dried over anhyd Na_2SO_4. The solution was concentrated under vacuum to an oil, which afforded after flash chromatography on silica gel (hexane then 20 : 1 hexane–EtOAc) **3** (9.5 g, 70%) as an oil: ^{1}H NMR ($CDCl_3$): δ 1.34, 1.45 (s and s, 6 H each, 2 CMe_2), 3.80–4.00 (m, 4 H, H-1,-1′,-6,-6′), 4.00–4.15 (m, 2 H, H-3,-4), 4.20–4.30 (m, 2 H, H-2,-5), 4.75 (s, 4 H, 2 CH_2Ph), and 7.17 (m, 10 H, 2 Ph).

3,4-Di-O-benzyl-D-mannitol (**4**).—A sample of **3** (4.0 g, 11.05 mmol), which was derived from a sample of diol **2** prepared from D-mannitol using the procedure described by Hertel et al.[4], was treated with 60% aq HOAc (100 mL) at 100°C for

3 h. The solution was cooled and concentrated to a syrupy residue, which crystallized after extensive drying under vacuum. Recrystallization from EtOAc–hexane afforded **4** (2.7 g, 84%): mp 77°C; $[\alpha]_D$ +42.7° (*c* 1.1, MeOH) {lit.[5] mp 74–75°C, $[\alpha]_D$ +48.4° (*c* 0.1, MeOH)}; ^{1}H NMR ($CDCl_3$): δ 3.10 (bd, 2 H, 2 OH), 3.60–3.80 (m, 6 H, H-1,-1′,-2,-5,-6,-6′), 3.90 (b, 2 H, 2 OH), 4.08 (d, 2 H, $J_{2,3} = J_{4,5} = 6.0$ Hz, H-3,-4), 4.55, 4.65 (d and d, 4 H, J_{gem} 11.5 Hz, 2 CH_2Ph), and 7.15 (m, 10 H, 2 Ph); ^{13}C NMR ($CDCl_3$): δ 63.50 (C-1,-6), 71.64 (C-2,-5), 73.90 (2 CH_2Ph), 77.76 (C-3,-4), 128.2, 128.3, 128.6, and 137.5 (2 Ph).

2,4-Di-O-benzyl-D-mannitol (**5**) *and 2,5-di-O-benzyl-D-mannitol* (**6**).—These compounds were isolated by silica gel chromatography of the product obtained by isopropylidenation of **1** using 2-methoxypropene as described by Debost et al.[3], followed by benzylation and *O*-deisopropylidenation. Compound **5** was recrystallized from EtOAc–hexane, and had R_f 0.25 (EtOAc): mp 74–75°C; $[\alpha]_D$ −56° (*c* 1.0, MeOH); ^{13}C NMR (50:1 $CDCl_3$–MeOH): δ 59.96 (C-1), 63.48 (C-6), 69.88 (C-3), 71.80 (C-5), 71.26, 73.38 (2 CH_2Ph), 77.14 (C-4), 78.46 (C-2), 127.90, 127.96, 128.39, 128.42, 137.80, and 137.93 (2 Ph). Anal. Calcd for $C_{20}H_{26}O_6$: C, 66.28; H, 7.23. Found: C, 66.09; H, 7.24.

Compound **6** was recrystallized from EtOAc and had R_f 0.40 (EtOAc); mp 121°C (lit.[6] 115°C; lit.[7] 119–120°C); $[\alpha]_D$ −7.1° (*c* 0.85, MeOH) [lit.[6] −8.5° (EtOH); lit.[7] −7° (*c* 0.63, EtOH)]; ^{13}C NMR (50:1 $CDCl_3$–MeOH): δ 61.08 (C-1,-6); 69.77 (C-3,-4), 72.49 (2 CH_2Ph), 79.70 (C-2,-5), 127.90, 128.42, and 137.65 (2 Ph). Anal. Calcd for $C_{20}H_{26}O_6$: C, 66.28; H, 7.23. Found: C, 66.03; H, 7.09.

Compound **5** was converted into 2,4-di-*O*-benzyl-1,6-di-*O*-trityl-D-mannitol as follows. To a solution of **5** (10 mg) in pyridine (0.5 mL) was added trityl chloride (30 mg). The mixture was stirred at room temperature for 2 days. Ice-cold water (2 mL) was added, and the precipitate was washed with water and dried. Purification by preparative TLC (4:1 hexane–EtOAc) afforded a sample of the di-*O*-trityl derivative: ^{1}H NMR ($CDCl_3$): δ 2.45 (d, 1 H, *J* 8.5 Hz, OH), 2.83 (b, 1 H, OH), 3.31–3.37 (m, 3 H), 3.54 (m, 1 H), 3.58 (m, 1 H), 3.90 (m, 1 H), 3.93–4.05 (m, 2 H), 4.22 and 4.65 (d and d, 2 H, J_{gem} 11.4 Hz, CH_2Ph), 4.25 and 4.37 (d and d, 2 H, J_{gem} 11.3 Hz, CH_2Ph), and 7.00–7.38 (m, 40 H, 8 Ph); ^{13}C NMR ($CDCl_3$): δ 61.34 (C-1), 64.54 (C-6), 69.80 (C-3), 70.89 (C-5), 71.88, 72.75 (2 CH_2Ph), 76.26 (C-4), 78.14 (C-2), 86.84, 86.98 (2 CPh_3), 127.11, 127.88, 127.95, 128.29, 128.75, 137.99, 138.36, 143.75, and 143.87 (2 CH_2Ph and 2 CPh_3).

3,4-Di-O-benzyl-D-fructose (**7**).—To a solution of compound **4** (0.66 g, 1.82 mmol) and bis(tributyltin)oxide (2.1 mL, 4.13 mmol) in dry CH_2Cl_2 (20 mL) was added dropwise a solution of bromine (0.21 mL) in CH_2Cl_2 (4 mL) at room temperature and under an atmosphere of argon. The mixture was stirred at room temperature for 1.5 h and then concentrated to a residue. Purification by flash chromatography (hexane and then EtOAc) gave **7** (0.56 g, 85%) as white crystals: ^{13}C NMR ($CDCl_3$): δ 62.35 (C-6, **7**α**f**), 62.62 (C-6, **7**β**p**), 63.06 (C-6, **7**β**f**), 64.59 (C-1, **7**α**f**), 65.24 (C-6, **7**β**f**), 65.53 (C-6, **7**β**p**), 67.30 (C-5, **7**β**p**), 72.14, 72.47, 73.00, 75.59 (CH_2Ph's), 75.21 (C-3, **7**β**p**), 78.94 (C-4, **7**β**p**), 81.77 (C-5, **7**β**f**), 81.80 (C-5,

7αf), 82.28 (C-4, **7α**f), 82.51 (C-4, **7β**f), 83.44 (C-3, **7β**f), 87.80 (C-3, **7α**f), 98.24 (C-2, **7β**p), 102.64 (C-2, **7β**f), 105.06 (C-2, **7α**f), 127.81, 127.96, 128.20, 128.27, 128.37, 128.46, 128.52, 128.60, 137.28, 137.69, 137.89, and 138.04 (Ph's).

Hydrogenolysis of **7**.—To a solution of **7** (100 mg, 0.28 mmol), consisting of three tautomeric forms, in MeOH (4 mL) was added 10% Pd–C (100 mg) and a drop of concd HCl, and the mixture was subjected to a hydrogen pressure (50 psig) for 3 h. The solution was concentrated to give D-fructose (**8**) as a glassy residue. The ^{13}C NMR spectrum in D_2O was identical to that of an authentic sample of D-fructose. Recrystallization from abs EtOH gave prisms (~ 10 mg): mp 103–104°C; $[\alpha]_D$ −88.1° (*c* 0.87, H_2O) {lit.[10] mp 102–104°C, $[\alpha]_D$ −92.5° (H_2O)}.

*6-Azido-3,4-di-*O*-benzyl-6-deoxy-*D*-mannitol* (**9**).—To a solution of **4** (0.82 g, 2.27 mmol) in dry pyridine (10 mL) was added *p*-toluenesulfonyl chloride (0.45 g, 2.31 mmol) at 0°C, and the mixture was stirred at that temperature for 7 h and then at room temperature overnight. Ice-cold water (30 mL) was added, and the mixture was extracted with $CHCl_3$ (2 × 40 mL). The organic solution was washed sequentially with water, aq $NaHCO_3$, and water, dried over anhyd Na_2SO_4, and evaporated. To a solution of the residue in 10:1 DMF–H_2O (20 mL) was added sodium azide (2.0 g), and the mixture was stirred at 100°C for 16 h. To the cooled mixture was added water (20 mL), and the mixture was extracted with $CHCl_3$ (50 mL). The organic solution was washed with water (2 × 50 mL) and dried over anhyd Na_2SO_4. The solution was concentrated under vacuum, and a trace of DMF was removed by codistillation with xylene. Column chromatography (EtOAc) gave **9** as crystals [0.44 g, 51% (two steps)] and **4** (0.1 g). Recrystallization of the sample of **9** from EtOAc–hexane gave white needles: mp 70.5°C; $[\alpha]_D$ +59.7° (*c* 0.44, MeOH); ν_{max} (KBr) 2130 cm^{-1} (N_3); ^1H NMR ($CDCl_3$): δ 2.18 (b, 1 H, OH), 3.29 (dd, 1 H, $J_{5,6}$ 5.0, $J_{6,6'}$ 12.5 Hz, H-6), 3.40 (s, 1 H, OH), 3.52 (dd, 1 H, $J_{5,6'}$ 3.0, $J_{6,6'}$ 12.5 Hz, H-6′), 3.67–3.87 (m, 5 H, H-1,-1′,-2,-5, and OH), 3.95 (m, 1 H, H-4), 4.05 (m, 1 H, H-3), 4.54, 4.58 (d and d, 2 H, J_{gem} 11.5 Hz, CH_2Ph), 4.60 (s, 2 H, CH_2Ph), and 7.32 (m, 10 H, 2 Ph); ^{13}C NMR ($CDCl_3$): δ 53.67 (C-6), 63.25 (C-1), 71.11 and 71.52 (C-2 and C-5), 73.87 (2 *C*H_2Ph), 77.20 (C-3,-4), 128.42, 128.58, 128.70, and 137.45 (2 Ph). Anal. Calcd for $C_{20}H_{25}N_3O_5 \cdot 0.33$ EtOAc: C, 61.47; H, 6.69; N, 10.08. Found: C, 61.47; H, 6.49; N, 10.06.

*6-Azido-3,4-di-*O*-benzyl-6-deoxy-β-*D*-fructofuranose* (**10**).—To a solution of **9** (0.43 g, 1.11 mmol) in dry CH_2Cl_2 (15 mL) was added bis(tributyltin)oxide (1.2 mL, 2.50 mmol), and the solution was stirred under an atmosphere of argon for 0.5 h. A solution of bromine (0.12 mL) in CH_2Cl_2 (5 mL) was added dropwise, and the mixture was stirred at room temperature for 1.5 h, and then concentrated to an oil. Purification by silica gel chromatography (hexane and then 1:1 hexane–EtOAc) gave a crystalline material (0.32 g, 75%) which was identified as consisting of the α and β anomers of 6-azido-3,4-di-*O*-benzyl-6-deoxy-D-fructofuranose. Recrystallization from EtOAc–hexane provided the β anomer **10** (0.16 g) as white needles: mp 76–77°C; $[\alpha]_D$ +44.3° (*c* 1.38, MeOH); ν_{max}(KBr) 2130 cm^{-1} (N_3); ^1H NMR ($CDCl_3$): δ 1.90 (t, 1 H, *J* 6.5 Hz, 1-OH), 3.38 (d, 2 H, $J_{5,6}$ 5.0 Hz, H-6,-6′), 3.61 (d,

2 H, *J* 6.5 Hz, H-1,-1'), 3.96–4.06 (m, 3 H, H-4,-5, and 2-OH), 4.16 (d, 1 H, $J_{3,4}$ 4.0 Hz, H-3), 4.48, 4.52 (d and d, 2 H, J_{gem} 12.0 Hz, CH_2Ph), and 7.30 (m, 10 H, 2 Ph); ^{13}C NMR ($CDCl_3$): δ 53.18 (C-6), 65.20 (C-1), 72.32, 73.27 (2 CH_2Ph), 80.13 (C-5), 82.79, 83.67 (C-3 and C-4), 103.46 (C-2), 127.83, 128.12, 128.24, 128.43, 128.58, 128.70, 128.77, 137.40, and 137.50 (2 Ph). Anal. Calcd for $C_{20}H_{23}N_3O_5$: C, 62.32; H, 6.01; N, 10.90. Found: C, 62.01; H, 6.03; N, 10.84.

*1,5-Dideoxy-1,5-imino-*D*-mannitol (1-deoxymannojirimycin)* (**11**).—To a solution of **10** (0.25 g, 0.65 mmol) in 3:1 MeOH–H_2O (10 mL) containing 0.1 N HCl was added 10% Pd–C (0.2 g), and the mixture was subjected to a hydrogen pressure (50 psig) at room temperature for 48 h. The solution was concentrated, and the residue was dissolved in a small amount of MeOH. Addition of Et_2O afforded **11** as its hydrochloride salt (123 mg, 93%): ^{13}C NMR (D_2O): δ 51.38 (C-1), 61.92 (C-6), 64.17 (C-5), 69.55 (C-2), 69.71 (C-3), and 76.23 (C-4). This salt, which was extremely hygroscopic, was passed through a column (10 × 0.8 cm) of ion-exchange resin (Amberlite CG-400, OH^- form), which was eluted with water. Lyophilization gave **11** (93 mg, 87%). Crystallization from MeOH–acetone–Et_2O provided white needles: mp 186–187°C (lit.[16–18] 185–187°C); $[\alpha]_D$ −39.4° (*c* 1.04, MeOH) [lit.[15] −34° (*c* 0.3, MeOH); lit.[16] −27.1° (*c* 0.14, H_2O); lit.[17] −39° (H_2O)]; ^1H NMR (D_2O): δ 2.40 (m, 1 H, H-5), 2.67 (dd, 1 H, $J_{1a,1e}$ 14.5, $J_{1e,2}$ 1.5 Hz, H-1e), 2.94 (dd, 1 H, $J_{1a,1e}$ 14.5, $J_{1a,2}$ 3.0 Hz, H-1a), 3.45–3.55 (m, 2 H, H-3,-4), 3.70 (d, 2 H, $J_{5,6}$ 5.0 Hz, H-6,-6'), and 3.92 (m, 1 H, H-2); ^{13}C NMR (D_2O): δ 52.03 (C-1), 64.27 (C-5), 64.55 (C-6), 72.17 (C-2), 73.03 (C-3), and 78.38 (C-4); CIMS(NH_3) *m/z*: 164 (100, M + H), 132 (6.9, M + H − MeOH), 110 (6.7), 74 (15.4), and 72 (19.5). Anal. Calcd for $C_6H_{13}NO_4$: C, 44.16; H, 8.02; N, 8.58. Found: C, 44.50; H, 7.94; N, 8.52.

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