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SYNTHESIS OF 2-ACETAMIDO-2,5-DIDEOXY-5-PHOSPHORYL-D-GLUCOPYRANOSE DERIVATIVES: NEW PHOSPHA-SUGAR ANALOGS OF *N*-ACETYL-D-GLUCOSAMINE

Tadashi Hanaya,* Masahiro Kawaguchi, Masakazu Sumi, Kazuo Makino, Keiko Tsukada, and Hiroshi Yamamoto[†]

Department of Chemistry, Faculty of Science, Okayama University, Tsushima-naka, Kita-ku, Okayama 700-8530, Japan. E-mail: hanaya@cc.okayama-u.ac.jp

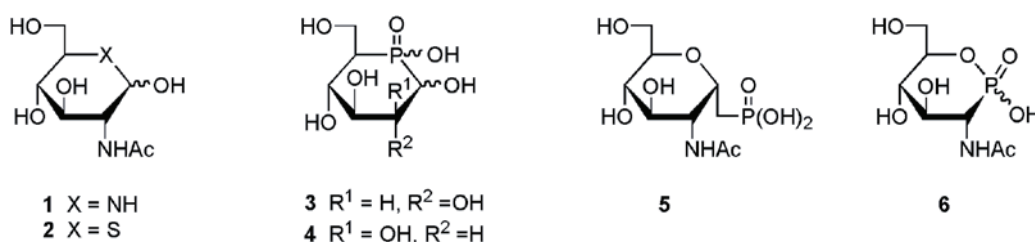
[†] School of Pharmacy, Shujitsu University, Nishigawara, Naka-ku, Okayama 703-8516, Japan

Abstract – Starting with *N*-acetyl-D-glucosamine, methyl 2-acetamido-3,6-di-*O*-benzyl-2-deoxy- β -D-*xyl*o-hexofuranosid-5-ulose (**18**) was prepared in 7 steps. The addition reaction of dimethyl phosphonate to **18**, followed by deoxygenation of its 5-hydroxy group, provided the 5-deoxy-5-dimethoxyphosphoryl-D-glucofuranoside derivative (**21a**). The hydride reduction of **21a**, followed by the action of hydrochloric acid and then hydrogen peroxide, afforded the first D-glucosamine analog (**23**) having a phosphoryl group in the hemiacetal ring. This was converted into the per-*O*-acetylated *N*-acetyl-D-glucosamine phospho-sugar (**25**), while the same treatment of the 5-deoxy-5-dimethoxyphosphoryl-L-idose dimethyl acetal derivative (**13b**) afforded the *N*-acetyl-L-idosamine phospho-sugar (**29**).

INTRODUCTION

Various sugar analogs containing nitrogen,¹ sulfur,² or phosphorus³ as a ring heteroatom have been prepared because of the wide interest in their chemical and biochemical properties. Heteroatom-in-the-ring sugar analogs of 2-amino- and 2-acetamido-2-deoxyhexopyranoses, which widely occur as a component of many natural products, have also attracted considerable interest. Azasugar (**1**)⁴ and thiasugar analogs (**2**)⁵ of *N*-acetyl-D-glucosamine, for example, have been prepared and *N*-acetyl-glucosaminidase inhibitory activity of the former has been reported.

In view of such a chemical modification by heteroatoms, we have prepared various sugar analogs having a phosphorus atom in the ring (phospha-sugar); *e.g.*, D-glucopyranose (**3**)⁶ and D-mannopyranose analogs (**4**).⁷ These phospha-sugar analogs are expected to be of interest in view of potential biological activities, such as glycosidase inhibitory activities⁸ and antitumor activities against leukemia cells.⁹ Meanwhile, as synthetic *N*-acetyl-D-glucosamine analogs having phosphorus attached to a sugar-carbon atom, the isosteric phosphonate analog of 1-phosphate (**5**)¹⁰ and the cyclic phosphonate analog (**6**)¹¹ have been prepared. We describe herein the first synthetic route to the *N*-acetyl-D-glucosamine phospha-sugar (**25**), by using our effective procedure¹² to introduce a phosphoryl group onto a sugar skeleton; namely addition of a phosphonate to an appropriate hexos-5-ulose derivative and the subsequent deoxygenation.



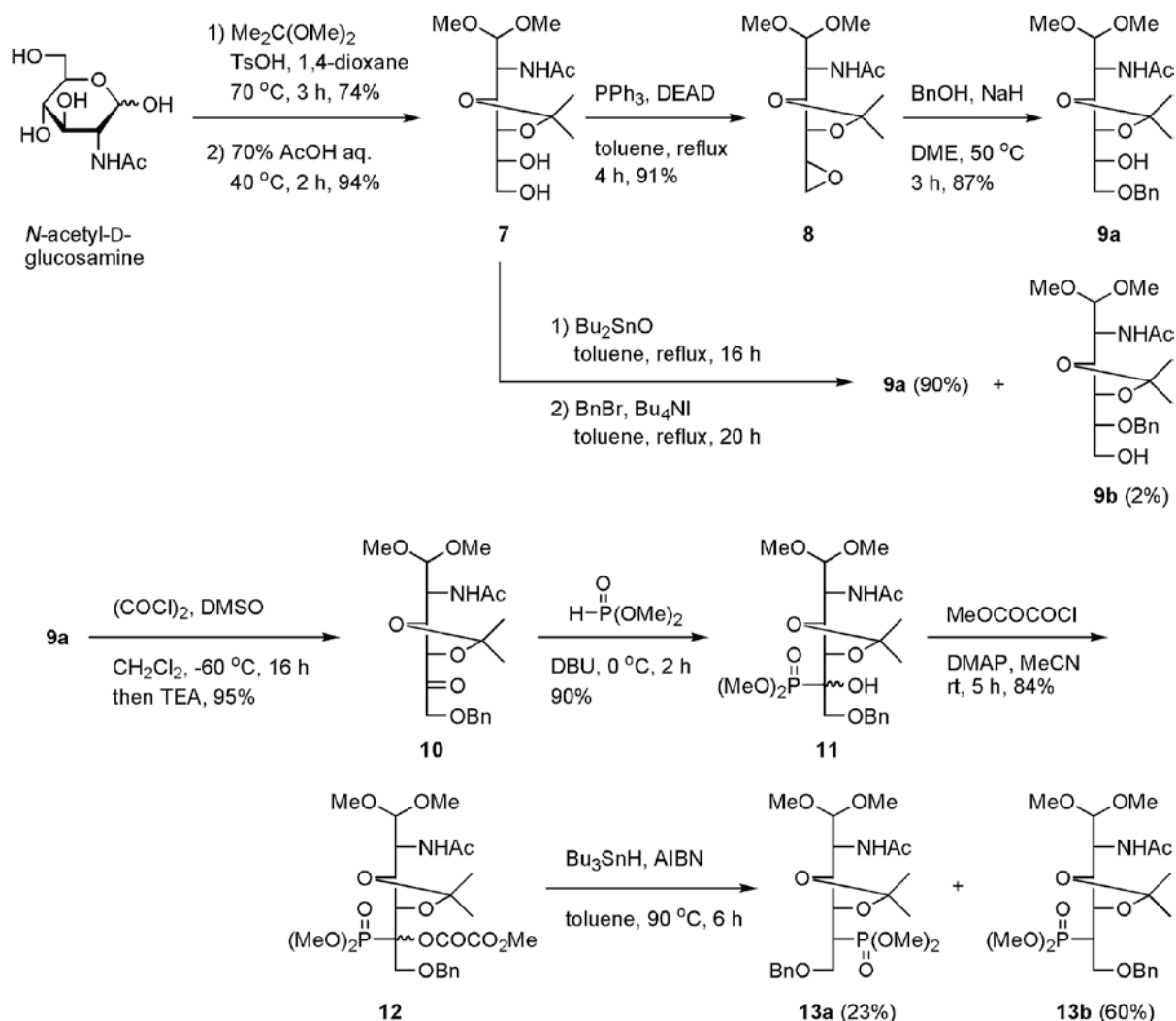
RESULTS AND DISCUSSION

For the preparation of the key 5-deoxy-5-dimethylphosphoryl-D-glucose precursors (**13a** and **21a**), two synthetic routes by starting with open-chain and furanose derivatives (**7** and **15**) of *N*-acetyl-D-glucosamine were employed (Scheme 1 and 3).

First, 2-acetamido-2-deoxy-3,4-*O*-isopropylidene-D-glucose dimethyl acetal (**7**) (available from *N*-acetyl-D-glucosamine in 2 steps)¹³ served as the starting material for preparation of the 5-ulose intermediate (**10**) to introduce a phosphoryl group, as illustrated in Scheme 1. The epoxidation of **7** under Mitsunobu's conditions afforded the 5,6-anhydro derivative (**8**) (91%), which was then treated with benzyl alcohol and sodium hydride in 1,2-dimethoxyethane (DME) to give the 6-*O*-benzyl compound (**9a**) in 87% yield. As an alternative way for preparation of **9a**, the 5,6-diol **7** was treated with dibutyltin oxide in refluxed toluene to give 5,6-*O*-stannylene acetal, which was subjected to the benzylation with benzyl bromide in the presence of tetrabutylammonium iodide in the same solvent,¹⁴ providing the 6-*O*-benzyl derivative (**9a**) (90% yield) together with a trace amount of the 5-*O*-benzyl isomer (**9b**) (2%). Swern oxidation of **9a** with oxalyl chloride-DMSO afforded the *D*-xylo-hexos-5-ulose dimethyl acetal (**10**) in 95%.

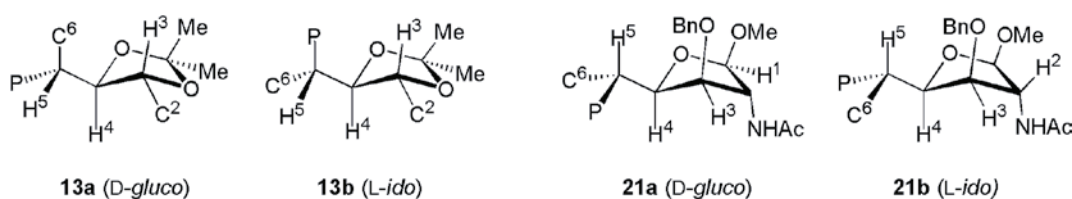
The addition reaction of dimethyl phosphonate to **10** in the presence of DBU gave the (5*R*)- and (5*S*)-5-*C*-dimethoxyphosphoryl-D-xylo-hexose derivatives (**11**) (26% and 54%, respectively).¹⁵ The diastereomeric mixture of **11** was converted to the methoxalyl esters (**12**) with methoxalyl chloride in the presence of 4-dimethylaminopyridine (DMAP) in 84% yield and then reduced with tributyltin hydride in the presence of AIBN, affording a 72:28 mixture of 5-deoxy products. On structural assignment of the

resulting two separable diastereoisomers by $^1\text{H-NMR}$, it turned out that the major isomer was not the expected 5-deoxy-5-dimethoxyphosphoryl-D-glucose derivative (**13a**) (23%) but the L-idose isomer (**13b**) (60%).



Scheme 1

The large $J_{3,4}$ values (8.5 and 8.2 Hz) of **13a,b** indicate an *anti* relationship of H-3/H-4 for both isomers. The D-*gluco* configuration for **13a** was assigned on the basis of the small $J_{4,p}$ (9.9 Hz) and $J_{4,5}$ (4.1 Hz) values and the presence of a long range coupling, $^4J_{3,p}$ (1.5 Hz)^{12,16} (Figure 1). Similarly, the L-*ido* configuration for **13b** was derived from the relatively large $J_{4,p}$ (18.2 Hz) and small $J_{4,5}$ (5.3 Hz) values.

Figure 1. The most favorable conformations for **13a,b** and **21a,b**.

(9.4 Hz) and the presence of a long-range coupling ${}^5J_{1,P}$ (1.2 Hz), whereas the *L-ido* configuration for **21b** was derived from the large $J_{4,5}$ value (10.6 Hz) and the presence of ${}^4J_{3,P}$ (1.2 Hz) and ${}^5J_{2,P}$ (1.5 Hz) (Figure 1).^{12,16}

Although the reduction from the open-chain 5-*O*-methoxalyl compound (**12**) preferentially gave the 5-deoxy-*L-ido* isomer (**13b**), the same reaction from the furanoside form (**20**) afforded 5-deoxy-*D-gluco* isomer (**21a**) as a major product. As this reaction proceeds via a radical intermediate formed by a homolytic cleavage of the O–C-5 bond, ratios of the 5-deoxy products (**13a:13b** and **21a:21b**) are not correlated to the diastereomeric ratios of the 5-*O*-methoxalyl precursors.¹² As for the predominant production of the *L-ido* isomer (**13b**) from **12**, we propose the rotamer **A** of the radical intermediate from the viewpoint of electronic factors (Figure 2). Namely, the opposition of the 5-phosphoryl group and electronegative 4-*O* atom diminishes their intramolecular electrostatic repulsion.¹⁸ Moreover, the alignment of the σ_{C4-C5} bond with the radical p orbital stabilizes the transition state by hyperconjugation. Meanwhile, as for the predominant production of the *D-gluco* isomer (**21a**) from **20**, another possible rotamer **B** was proposed, taking into account both the electrostatic repulsion between two electronegative groups and the steric repulsion between C-6 and the 3-*O*-benzyl group.¹⁹

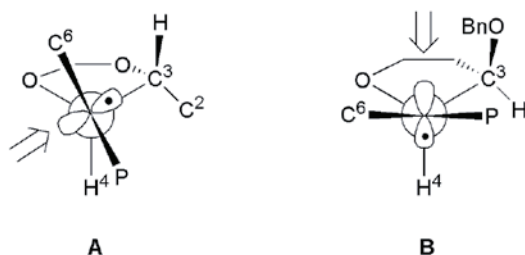
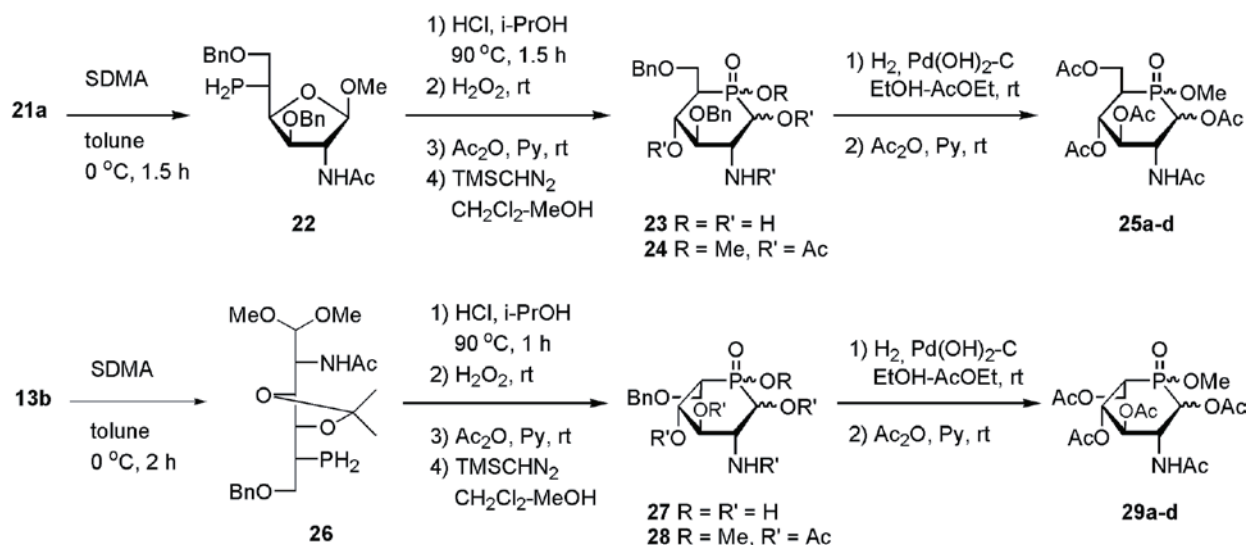


Figure 2. The most plausible conformations for the radical intermediates **A** (from **12**) and **B** (from **20**) and directions of the reduction.

The major product (**21a**) was then reduced with sodium dihydrobis(2-methoxyethoxy)aluminate (SDMA) to give the 5-phosphino derivative (**22**), which was immediately treated with hydrochloric acid at 90 °C and then oxidized with hydrogen peroxide to afford 2-amino-3,6-di-*O*-benzyl-2,5-dideoxy-5-hydroxyphosphoryl- α,β -*D-gluco*pyranoses (**23**) (Scheme 3).

For the purpose of purification and characterization, compounds **23** were converted to the corresponding 1,2,4-triacetyl-5-methoxyphosphoryl derivatives (**24**) by treatment with acetic anhydride-pyridine and then trimethylsilyldiazomethane. Debenzoylation of **24** by the catalytic hydrogenation over 20% Pd(OH)₂-C, followed by acetylation, afforded the fully acetylated *N*-acetyl-*D-gluco*samine phospho-sugar (**25**). By purification on a silica gel column, the 5-deoxy-5-[(*R*)-methoxyphosphoryl]- α -*D-gluco*pyranose (**25a**) (7.5% overall yield from **21a**), its β -anomer (**25b**) (2.7%), 5-[(*S*)-methoxyphosphoryl]- α -*D-gluco*pyranose (**25c**) (19%), and its β -anomer (**25d**) (2.3%) were obtained.

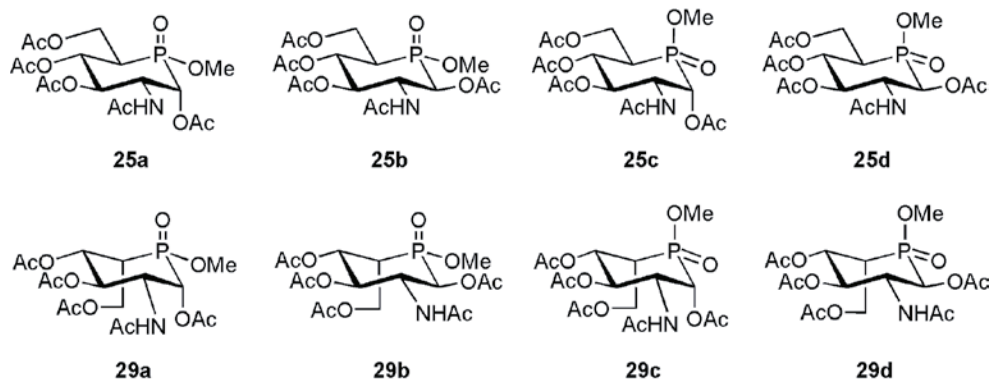


Scheme 3

The similar treatment of the L-idose dimethyl acetal derivative (**13b**) afforded 2-amino-3,6-di-O-benzyl-2,5-dideoxy-5-hydroxyphosphoryl- α,β -L-idopyranoses (**27**) via 5-phosphino compound **26**. The L-idopyranose analogs **27** were also converted to *N*-acetyl-L-idosamine phospho-sugar (**29**) via **28**: the 5-deoxy-5-[(*R*)-methoxyphosphoryl]- β -L-idopyranose (**29a**) (3.4% overall yield from **13b**), its α -anomer (**29b**) (8.3%), 5-[(*S*)-methoxyphosphoryl]- β -L-glucopyranose (**29c**) (5.4%), and its α -anomer (**29d**) (3.0%).

The precise structures of **25a-d** and **29a-d** were established by the analysis of their $^1\text{H-NMR}$ spectra; for all the assignments of the signals, see Table 1. The D-glucopyranose configuration of **25a-d** are derived from the large values of $J_{4,5}$ (11–12 Hz). As for anomeric orientation of C-1, the large $J_{1,2}$ values (10.5 Hz) of **25b,d** indicate the axial H-1 orientation, whereas the small $J_{1,2}$ values (2.6 Hz) of **25a,c** show the equatorial H-1 configuration.³ With regard to the orientation of the ring P=O group, a downfield shift (0.2–0.3 ppm) of H-2,4 for **25a,b** compared with those of **25c,d** indicates the axial P=O orientation for the former and the equatorial P=O orientation for the latter. In contrast, the small values of $J_{4,5}$ (5–6 Hz) for **29a-d** indicate the L-idopyranose structure and their structural assignments were made by similar characteristic tendency of the corresponding $J_{1,2}$ values and H-2,4 chemical shifts for **25a-d**.

Present work thus demonstrates a convenient way for preparation of 2-acetamido-2,5-dideoxy-5-phosphoryl-D-glucopyranose from appropriate intermediates. Extension of this work including applications of these findings in synthesizing other phospho-sugar analogs, as well as biological evaluation of *N*-acetyl-D-glucosamine phospho-sugars, is anticipated to be highly of interest.

Table 1. ^1H and ^{31}P NMR Parameters for Compounds **25a–d** and **29a–d** in CDCl_3

Com- pound	Chemical shifts / δ											^{31}P
	H-1	H-2	H-3	H-4	H-5	H-6	H'-6	POMe	HN-2 ^a	Ac-1,2,3,4,6, ^b		
25a	5.45	4.85	5.19	5.56	2.57	4.43	4.35	3.75	5.68	2.23, 2.08, 2.05, 2.04, 1.91	38.79	
25b	5.11	4.79	4.97	5.52	2.42	4.44	4.41	3.85	5.60	2.15, 2.09, 2.07, 2.03, 1.92	37.25	
25c	5.58	4.59	5.14	5.39	2.65	4.62	4.24	3.93	5.72	2.25, 2.07, 2.04, 2.04, 1.91	37.29	
25d	5.27	4.57	5.00	5.37	2.43	4.59	4.31	3.97	5.65	2.14, 2.08, 2.03, 2.02, 1.92	35.48	
29a	5.45	4.67	5.35	5.52	2.98	4.56	4.36	3.84	c	2.20, 2.11, 2.08, 2.07, 1.95	37.50	
29b	5.48	4.56	5.31	5.33	2.83	4.43	4.40	3.98	5.48	2.24, 2.15, 2.08, 2.04, 1.92	36.96	
29c	5.54	4.67	5.28	5.30	2.91	4.56	4.46	3.90	c	2.22, 2.10, 2.09, 2.04, 1.96	36.85	
29d	5.79	4.45	5.69	5.25	2.59	4.50	4.35	3.97	6.09	2.22, 2.06, 2.01, 1.91, 1.85	36.85	

	Coupling constants / Hz													
	$J_{1,2}$	$J_{1,P}$	$J_{2,3}$	$J_{2,P}$	$J_{3,4}$	$J_{4,5}$	$J_{4,P}$	$J_{5,6}$	$J_{5,6'}$	$J_{5,P}$	$J_{6,6'}$	$J_{6,P}$	$J_{6',P}$	J_{POMe}
25a	2.6	13.2	11.2	0	9.6	12.2	1.8	5.9	4.7	13.8	12.0	16.4	12.9	10.9
25b	10.5	5.6	10.6	2.4	9.6	11.0	2.0	5.0	6.0	13.0	11.8	14.5	16.0	11.0
25c	2.6	14.1	11.1	0	9.7	11.7	1.8	4.4	3.5	13.9	12.0	22.0	10.0	10.6
25d	10.5	3.0	10.0	2.5	9.8	12.0	2.0	5.0	4.1	12.5	11.8	20.0	11.5	10.6
29a^d	5.3	11.2	10.0	c	10.8	5.3	c	4.1	7.6	25.5	11.7	c	10.1	10.9
29b	11.4	4.4	9.5	3.5	8.8	5.9	c	2.9	2.9	25.2	11.7	9.2	0	10.6
29c^e	3.5	10.8	9.5	c	8.5	5.0	c	4.7	7.3	21.4	11.7	c	10.9	10.9
29d	11.2	5.0	10.2	c	10.6	5.9	1.0	3.2	4.1	25.2	11.5	c	7.9	10.6

^a $J_{2,\text{NH}} = 8.5\text{--}8.8$ Hz. ^b The assignment of acetyl signals may be interchanged. ^c Uncertain because of overlapping with other signals. ^d $J_{1,5} = 0.8$ Hz. ^e $J_{1,5} = 1.5$ Hz.

EXPERIMENTAL

All reactions were monitored by TLC (Merck silica gel 60F, 0.25 mm) with an appropriate solvent system [(A) AcOEt and (B) 1:9 EtOH-AcOEt]. Column chromatography was performed with Daiso Silica Gel IR-60/210w. Components were detected by exposing the plates to UV light and/or spraying them with 20% sulfuric acid–ethanol (with subsequent heating). Optical rotations were measured with a Jasco P-1020 polarimeter in CHCl₃. The NMR spectra were measured in CDCl₃ with Varian 600-System (600 MHz for ¹H, 151 MHz for ¹³C, 243 MHz for ³¹P) spectrometer at 23 °C. Chemical shifts are reported as δ values relative to CHCl₃ (7.26 ppm as an internal standard for ¹H), CDCl₃ (77.0 ppm as an internal standard for ¹³C), and 85% phosphoric acid (0 ppm as an external standard for ³¹P). The assignments of ¹³C signals were made with the aid of 2D HSQC measurements. The MS spectra were measured on a VG-70SE instrument.

2-Acetamido-5,6-anhydro-2-deoxy-3,4-*O*-isopropylidene-D-glucose dimethyl acetal (**8**).

To a solution of **7** (¹³ (300 mg, 0.976 mmol) and triphenylphosphine (310 mg, 1.18 mmol) in dry toluene (10 mL) was added DEAD (40% in toluene, 0.470 mL, 1.18 mmol). The mixture was refluxed for 4 h and evaporated in vacuo. The residue was purified by column chromatography with AcOEt as an eluant to give **8** (257 mg, 91%) as colorless needles: mp 102–103 °C (from AcOEt-hexane): *R*_f = 0.39 (A); [α]_D²² +4.55 (*c* 1.28, CHCl₃); ¹H-NMR δ = 1.41, 1.42 (3H each, s, CMe₂), 2.03 (3H, s, NAc), 2.69 (1H, dd, *J*_{6,6'} = 4.7, *J*_{5,6} = 2.6 Hz, H'-6), 2.83 (1H, t, *J*_{5,6} = 4.1 Hz, H-6), 3.79 (1H, td, *J*_{4,5} = 4.7 Hz, H-5), 3.36, 3.42 (3H each, 2s, MeO-1), 3.69 (1H, dd, *J*_{3,4} = 7.9 Hz, H-4), 4.21 (1H, dd, *J*_{2,3} = 2.1 Hz, H-3), 4.26 (1H, ddd, *J*_{2,NH} = 9.7, *J*_{1,2} = 5.9 Hz, H-2), 4.40 (1H, d, H-1), 5.85 (1H, d, HN-2); ¹³C NMR δ = 23.36 (CH₃CO), 26.66 and 26.85 (CMe₂), 45.04 (C-6), 49.46 (C-2), 51.39 (C-5), 53.28 and 55.52 (MeO-1), 75.77 (C-3), 77.10 (C-4), 103.03 (C-1), 109.91 (CMe₂), 169.96 (CH₃CO). Anal. Calcd for C₁₃H₂₃NO₆: C, 53.97; H, 8.01. Found: C, 53.90; H, 8.04.

2-Acetamido-6-*O*-benzyl-2-deoxy-3,4-*O*-isopropylidene-D-glucose dimethyl acetal (**9a**) and its 5-*O*-benzyl analog (**9b**).

A. From 8. To a suspension of sodium hydride (60% in mineral oil, 560 mg, 14.0 mmol) and benzyl alcohol (2.20 mL, 21.3 mmol) in DME (5.0 mL) was added a solution of **8** (2.02 g, 6.98 mmol) in DME (5.0 mL) at 0 °C. The mixture was stirred at 50 °C for 3 h, diluted with saturated aqueous NH₄Cl (20 mL), and extracted with CHCl₃ three times. The combined organic layers were washed with water, dried (Na₂SO₄), and concentrated in vacuo. The residue was purified by column chromatography with 3:1 AcOEt-hexane as an eluant to give **9a** (2.44 g, 88%) as colorless needles.

B. From 7. To a solution of **7** (1.85 g, 6.02 mmol) in toluene (50 mL) was added dibutyltin oxide (1.80

g, 7.23 mmol) and then the suspension was refluxed under Dean-Stark trap for 16 h. After removal of the trap, benzyl bromide (1.40 mL, 11.8 mmol) and tetrabutylammonium iodide (1.10 g, 2.98 mmol) were added and the mixture was refluxed for 20 h. The mixture was evaporated in vacuo and the residue was separated by column chromatography on silica gel to give **9a** (2.15 g, 90%) and **9b** (45 mg, 2%).

9a: Colorless needles: 97–99 °C (from AcOEt-hexane); $R_f = 0.44$ (*A*); $[\alpha]_D^{20} +13.3$ (*c* 1.23, CHCl₃); ¹H NMR $\delta = 1.37$ (6H, s, CMe₂), 2.03 (3H, s, NAc), 3.10 (1H, br s, HO-5), 3.32, 3.39 (3H each, 2s, MeO-1), 3.55 (1H, dd, $J_{6,6'} = 9.8$, $J_{5,6'} = 5.8$ Hz, H'-6), 3.65 (1H, t, $J_{3,4} = 8.2$, $J_{4,5} = 8.0$ Hz, H-4), 3.70 (1H, dd, $J_{5,6} = 2.8$ Hz, H-6), 3.79 (1H, ddd, H-5), 4.27 (1H, dd, $J_{2,3} = 1.5$ Hz, H-3), 4.42 (1H, d, $J_{1,2} = 6.7$ Hz, H-1), 4.47 (1H, ddd, $J_{2,NH} = 9.5$ Hz, H-2), 4.58 (2H, s, CH₂O-6), 5.85 (1H, d, HN-2), 7.27 [1H, t, $J_{m,p} = 7.4$ Hz, Ph(*p*)], 7.34–7.38 [4H, m, Ph(*o,m*)]. Anal. Calcd for C₂₀H₃₁NO₇: C, 60.44; H, 7.86. Found: C, 60.61; H, 7.90.

9b: Colorless syrup; $R_f = 0.41$ (*A*); ¹H NMR $\delta = 1.38$, 1.39 (3H each, s, CMe₂), 2.03 (3H, s, NAc), 2.90 (1H, br s, HO-6), 3.28, 3.38 (3H each, 2s, MeO-1), 3.69 (1H, m, H-5), 3.72–3.76 (2H, m, H,H'-6), 3.90 (1H, d, $J_{3,4} = 8.5$, $J_{4,5} = 4.4$ Hz, H-4), 4.36 (1H, ddd, $J_{2,NH} = 9.7$, $J_{1,2} = 6.5$, $J_{2,3} = 1.2$ Hz, H-2), 4.37 (1H, dd, H-3), 4.40 (1H, d, H-1), 4.67, 4.71 (1H each, 2d, $^2J = 11.7$ Hz, CH₂O-5), 5.88 (1H, d, HN-2), 7.28 [1H, t, $J_{m,p} = 7.5$ Hz, Ph(*p*)], 7.34 [2H, t, $J_{o,m} = 7.5$ Hz, Ph(*m*)], 7.38 [2H, d, Ph(*o*)].

2-Acetamido-6-O-benzyl-2-deoxy-3,4-O-isopropylidene-D-xylo-hexos-5-ulose dimethyl acetal (**10**).

To a solution of oxalyl chloride (1.70 mL, 19.5 mmol) in CH₂Cl₂ (4.0 mL) was added DMSO (2.80 mL, 39.4 mmol) in CH₂Cl₂ (8.0 mL) at –60 °C. After stirring for 30 min, a solution of **9a** (2.56 g, 6.44 mmol) in CH₂Cl₂ (8 mL) was added. The mixture was stirred for 16 h and then TEA (9.0 mL, 64.4 mmol) was added. The mixture was stirred for 1 h, diluted with CHCl₃, and washed with saturated aqueous NaCl. The aqueous layer was extracted with CHCl₃. The combined organic layers were washed with water, dried (Na₂SO₄), and evaporated in vacuo. The residue was purified by column chromatography with AcOEt to give **10** (2.41 g, 95%) as colorless needles: mp 96–97 °C (from AcOEt-hexane); $R_f = 0.46$ (*A*); $[\alpha]_D^{20} -1.41$ (*c* 1.62, CHCl₃); ¹H NMR $\delta = 1.32$, 1.43 (3H each, 2s, CMe₂), 2.04 (3H, s, NAc), 3.34, 3.40 (3H each, 2s, MeO-1), 4.23 (1H, d, $J_{3,4} = 7.3$ Hz, H-4), 4.33, 4.46 (1H each, 2d, $J_{6,6'} = 18.5$ Hz, H₂-6), 4.38 (1H, d, $J_{1,2} = 5.9$ Hz, H-1), 4.45 (1H, dd, $J_{2,3} = 1.8$ Hz, H-3), 4.49 (1H, ddd, $J_{2,NH} = 9.7$ Hz, H-2), 4.59, 4.63 (1H each, 2d, $^2J = 11.7$ Hz, CH₂O-6), 5.79 (d, 1H, HN-2), 7.27 [1H, t, $J_{m,p} = 7.4$ Hz, Ph(*p*)], 7.34–7.38 [4H, m, Ph(*o,m*)]; ¹³C NMR $\delta = 23.37$ (CH₃CO), 25.88 and 26.64 (CMe₂), 49.77 (C-2), 53.36 and 55.05 (MeO-1), 72.61 (CH₂O-6), 73.28 (C-6), 75.64 (C-3), 80.33 (C-4), 102.87 (C-1), 111.02 (CMe₂), 127.99 [Ph(*p*)], 128.07 [Ph(*o*)], 128.48 [Ph(*m*)], 137.04 [Ph(*ipso*)], 170.15 (CH₃CO), 205.67 (C-5). Anal. Calcd for C₂₀H₂₉NO₇: C, 60.74; H, 7.39. Found: C, 60.61; H, 7.42.

(5R)- and (5S)-2-Acetamido-6-O-benzyl-2-deoxy-5-C-dimethoxyphosphoryl-3,4-O-isopropylidene-D-xylo-hexose dimethyl acetals (11).

To a solution of **10** (2.10 g, 5.31 mmol) in dimethyl phosphonate (25 mL) was added DBU (1.60 mL, 10.7 mmol) at 0 °C under argon. After stirring for 2 h at 0 °C, the mixture was treated with saturated aqueous NH₄Cl at rt for 0.5 h and then extracted with CHCl₃ three times. The combined organic layers were washed with water, dried (Na₂SO₄), and concentrated in vacuo. The residue was separated by column chromatography with 1:9 EtOH-AcOEt to give (5R)-**11** (958 mg, 36%) and (5S)-**11** (1.44 g, 54%).

(5R)-**11**: Colorless syrup; $R_f = 0.30$ (B); $[\alpha]_D^{22} +4.17$ (c 1.37, CHCl₃); ¹H NMR $\delta = 1.36, 1.38$ (3H each, 2s, CMe₂), 2.05 (3H, s, NAc), 3.30, 3.33 (3H each, 2s, MeO-1), 3.80, 3.82 (3H each, 2d, $J_{\text{POMe}} = 10.6$ Hz, POMe), 3.85 (1H, dd, $J_{6',\text{P}} = 10.9, J_{6,6'} = 9.9$ Hz, H-6'), 3.87 (1H, dd, $J_{6,\text{P}} = 13.8$ Hz, H-6'), 4.02 (1H, t, $J_{4,\text{P}} = 8.5, J_{3,4} = 8.2$ Hz, H-4), 4.06 (1H, br s, HO-5), 4.37 (1H, d, $J_{1,2} = 6.5$ Hz, H-1), 4.49 (1H, ddd, $J_{2,\text{NH}} = 9.7, J_{2,3} = 1.1$ Hz, H-2), 4.59, 4.66 (1H each, 2d, $^2J = 11.9$ Hz, CH₂O-6), 4.70 (1H, dt, $^3J_{3,\text{P}} = 1.0$ Hz, H-3), 5.84 (1H, d, HN-2), 7.27 [1H, t, $J_{m,\text{p}} = 7.6$ Hz, Ph(*p*)], 7.33 [2H, t, $J_{o,m} = 7.5$ Hz, Ph(*m*)], 7.37 [2H, d, Ph(*o*)]; ³¹P NMR $\delta = 24.77$.

(5S)-**11**: Colorless needles; mp 121–123 °C (from AcOEt); $R_f = 0.40$ (B); $[\alpha]_D^{22} +12.8$ (c 0.97, CHCl₃); ¹H NMR $\delta = 1.37, 1.44$ (3H each, 2s, CMe₂), 1.98 (3H, s, NAc), 3.28, 3.36 (3H each, 2s, MeO-1), 3.72–3.82 (3H, m, H₂-6, HO-5), 3.75, 3.80 (3H each, 2d, $J_{\text{POMe}} = 10.6$ Hz, POMe), 4.03 (1H, dd, $J_{4,\text{P}} = 19.1, J_{3,4} = 8.8$ Hz, H-4), 4.39 (1H, d, $J_{1,2} = 6.5$ Hz, H-1), 4.46 (1H, ddd, $J_{2,\text{NH}} = 9.7, J_{2,3} = 1.2$ Hz, H-2), 4.57, 4.65 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-6), 4.79 (1H, dd, H-3), 5.88 (1H, d, HN-2), 7.26 [1H, t, $J_{m,\text{p}} = 7.5$ Hz, Ph(*p*)], 7.32 [2H, t, $J_{o,m} = 7.5$ Hz, Ph(*m*)], 7.37 [2H, d, Ph(*o*)]; ³¹P NMR $\delta = 24.75$. Anal. Calcd for C₂₂H₃₆NO₁₀P: C, 52.27; H, 7.18. Found: C, 52.47; H, 7.13.

(5R)- and (5S)-2-Acetamido-6-O-benzyl-2-deoxy-5-C-dimethoxyphosphoryl-5-O-methoxalyl-3,4-O-isopropylidene-D-xylo-hexose dimethyl acetals (12).

Methoxalyl chloride (0.330 mL, 3.59 mmol) was added to a solution of **11** (40:60 diastereomeric mixture, 936 mg, 1.79 mmol) and DMAP (608 mg, 4.98 mmol) in dry MeCN (10 mL) at 0 °C. The mixture was stirred at rt for 5 h under argon and then concentrated in vacuo. The residue was treated with saturated aqueous NH₄Cl and extracted with CHCl₃. The combined organic layers were washed with water, dried (Na₂SO₄), and evaporated in vacuo. The residue was purified by column chromatography with AcOEt to give an inseparable mixture (40:60) of (5R)- and (5S)-**12** (889 mg, 84%) as a colorless syrup: $R_f = 0.45$ (B).

(5R)-**12**: ¹H NMR $\delta = 1.40, 1.42$ (3H each, 2s, CMe₂), 2.03 (1H, s, NAc), 3.29, 3.30 (3H each, 2s, MeO-1), 3.80, 3.81 (3H each, 2d, $J_{\text{POMe}} = 11.0$ Hz, POMe), 3.89 (3H, s, CO₂Me), 4.21 (1H, dd, $J_{6',\text{P}} =$

15.9, $J_{6,6'} = 9.7$ Hz, H'-6), 4.28 (1H, dd, $J_{6,P} = 8.2$ Hz, H-6), 4.30 (1H, d, $J_{1,2} = 6.5$ Hz, H-1), 4.38 (1H, dd, $J_{3,4} = 8.2$, $J_{4,P} = 7.4$ Hz, H-4), 4.56, 4.60 (1H each, 2d, $^2J = 11.7$ Hz, CH₂O-6), 4.60 (1H, ddd, $J_{2,NH} = 10.0$, $J_{2,3} = 1.0$ Hz, H-2), 4.80 (1H, dd, H-3), 5.77 (1H, d, HN-2), 7.26 [1H, t, $J_{m,p} = 7.4$ Hz, Ph(*p*)], 7.29–7.34 [4H, m, Ph(*o,m*)]; ^{31}P NMR $\delta = 19.08$.

(5*S*)-**12**: ^1H NMR $\delta = 1.42$, 1.49 (3H each, 2s, CMe₂), 2.04 (1H, s, NAc), 3.16, 3.18 (3H each, 2s, MeO-1), 3.77, 3.80 (3H each, 2d, $J_{\text{POMe}} = 10.9$ Hz, POMe), 3.89 (3H, s, CO₂Me), 4.01 (1H, dd, $J_{6,6'} = 10.6$, $J_{6,P} = 2.9$ Hz, H'-6), 4.16 (1H, dd, $J_{3,4} = 7.9$, $J_{4,P} = 5.3$ Hz, H-4), 4.28 (1H, d, $J_{1,2} = 6.5$ Hz, H-1), 4.37 (1H, t, $J_{6,P} = 10.2$ Hz, H-6), 4.47, 4.63 (1H each, 2d, $^2J = 11.7$ Hz, CH₂O-6), 4.58 (1H, ddd, $J_{2,NH} = 10.0$, $J_{2,3} = 1.0$ Hz, H-2), 4.69 (1H, dd, H-3), 5.79 (1H, d, HN-2), 7.24–7.30 (5H, m, Ph); ^{31}P NMR $\delta = 19.16$. Anal. Calcd for C₂₅H₃₈NO₁₃P: C, 50.76; H, 6.47. Found: C, 50.60; H, 6.51.

2-Acetamido-6-*O*-benzyl-2,5-dideoxy-5-dimethoxyphosphoryl-3,4-*O*-isopropylidene-D-glucose dimethyl acetal (**13a**) and its L-idose analog (**13b**).

To a solution of **12** (900 mg, 1.51 mmol) in toluene (6 mL), a solution of AIBN (130 mg, 0.792 mmol) and tributyltin hydride (0.850 mL, 3.16 mmol) in dry toluene (7 ml) was dropwise added at 90 °C under argon. The mixture was stirred at the same temperature for 6 h and then concentrated in vacuo. The residue was separated by column chromatography with 1:9 EtOH-AcOEt to give **13a** (169 mg, 23%) and **13b** (442 mg, 60%).

13a: Colorless syrup; $R_f = 0.28$ (*B*); $[\alpha]_{\text{D}}^{24} +1.79$ (*c* 2.47, CHCl₃); ^1H NMR $\delta = 1.33$, 1.39 (3H each, 2s, CMe₂), 2.02 (3H, s, NAc), 2.47 (1H, dddd, $J_{5,P} = 23.8$ Hz, $J_{5,6} = 6.8$, $J_{4,5} = 4.1$, $J_{5,6'} = 3.2$, H-5), 3.30, 3.31 (3H each, 2s, MeO-1), 3.725, 3.73 (3H each, 2d, $J_{\text{POMe}} = 10.9$ Hz, POMe), 3.79 (1H, ddd, $J_{6',P} = 15.6$, $J_{6,6'} = 10.0$ Hz, H'-6), 3.89 (1H, ddd, $J_{6,P} = 7.6$ Hz, H-6), 4.04 (1H, ddd, $J_{4,P} = 9.9$, $J_{3,4} = 8.5$ Hz, H-4), 4.33 (1H, d, $J_{1,2} = 5.9$ Hz, H-1), 4.35 (1H, ddd, $J_{2,NH} = 8.5$, $J_{2,3} = 1.5$ Hz, H-2), 4.46 (1H, dt, $^4J_{3,P} = 1.5$ Hz, H-3), 4.49, 4.55 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-6), 5.77 (1H, d, HN-2), 7.26 [1H, t, $J_{m,p} = 7.5$ Hz, Ph(*p*)], 7.34–7.38 [4H, m, Ph(*o,m*)]; ^{13}C NMR $\delta = 23.35$ (CH₃CO), 26.88 and 27.07 (CMe₂), 39.36 (d, $^1J_{5,P} = 136.9$ Hz, C-5), 48.15 (C-2), 52.69 and 52.73 [2d, $^2J_{\text{C,P}} = 6.7$ Hz, P(OMe)₂], 52.95 and 54.93 (MeO-1), 64.94 (C-6), 73.10 (CH₂O-6), 74.32 (d, $^2J_{4,P} = 2.8$ Hz, C-4), 76.76 (d, $^3J_{3,P} = 8.4$ Hz, C-3), 103.36 (C-1), 108.62 (CMe₂), 127.54 [Ph(*p*)], 127.71 [Ph(*o*)], 128.25 [Ph(*m*)], 137.89 [Ph(*ipso*)], 169.79 (CH₃CO); ^{31}P NMR $\delta = 30.31$.

13b: Colorless needles: mp 97–99 °C, $R_f = 0.38$ (*B*); $[\alpha]_{\text{D}}^{24} +16.6$ (*c* 2.12, CHCl₃); ^1H NMR $\delta = 1.38$, 1.41 (3H each, 2s, CMe₂), 1.99 (3H, s, NAc), 2.52 (1H, dddd, $J_{5,P} = 22.0$, $J_{5,6'} = 7.6$, $J_{4,5} = 5.3$, $J_{5,6} = 3.8$ Hz, H-5), 3.28, 3.34 (3H each, 2s, MeO-1), 3.71, 3.72 (3H each, 2d, $J_{\text{POMe}} = 11.0$ Hz, POMe), 3.75 (1H, ddd, $J_{6',P} = 15.3$, $J_{6,6'} = 10.0$ Hz, H'-6), 3.85 (1H, ddd, $J_{6,P} = 13.8$ Hz, H-6), 4.04 (1H, ddd, $J_{4,P} = 18.2$, $J_{3,4} = 8.2$ Hz, H-4), 4.35 (1H, d, $J_{1,2} = 6.2$ Hz, H-1), 4.40 (1H, dd, $J_{2,NH} = 9.7$, $J_{2,3} = 1.7$ Hz, H-2), 4.53 (1H, dd,

H-3), 4.54 (2H, s, CH₂O-6), 5.78 (1H, d, HN-2), 7.26 [1H, t, $J_{m,p} = 7.4$ Hz, Ph(*p*)], 7.33 [2H, t, $J_{o,m} = 7.4$ Hz, Ph(*m*)], 7.36 [2H, d, Ph(*o*)]; ¹³C NMR δ = 23.36 (CH₃CO), 26.89 and 27.06 (CMe₂), 40.56 (d, $^1J_{5,P} = 138.6$ Hz, C-5), 48.58 (C-2), 52.37 and 52.56 [2d, $^2J_{C,P} = 6.7$ Hz, P(OMe)₂], 52.85 and 55.21 (MeO-1), 66.63 (C-6), 72.93 (CH₂O-6), 74.17 (d, $^2J_{4,P} = 4.5$ Hz, C-4), 77.42 (d, $^3J_{3,P} = 7.3$ Hz, C-3), 103.50 (C-1), 108.74 (CMe₂), 127.52 [Ph(*p*)], 127.71 [Ph(*o*)], 128.24 [Ph(*m*)], 137.87 [Ph(*ipso*)], 169.72 (CH₃CO); ³¹P NMR δ = 29.51. Anal. Calcd for C₂₂H₃₆NO₉P: C, 53.98; H, 7.41. Found: C, 54.11; H, 7.37.

Methyl 2-acetamido-3-*O*-benzyl-2-deoxy-β-D-glucofuranoside (15).⁵

The following modification of the literature procedures⁴ was made. The oxazoline **14**¹⁷ (3.93 g, 11.8 mmol) was dissolved in dry MeOH (40 mL) containing 4M HCl (in dioxane, 0.032 mL). The mixture was stirred at rt for 5 h and neutralized with Amberlite-IRA96SB at 0 °C. The resin was filtered off and the filtrate was evaporated in vacuo to give a crude syrup (4.25 g) of methyl 2-acetamido-3-*O*-benzyl-2-deoxy-5,6-*O*-isopropylidene-β-D-glucofuranoside: $R_f = 0.59$ (A).

The above syrup was dissolved in 70% aqueous acetic acid (50 ml) and the mixture was stirred at 40 °C for 6 h. Then the mixture was concentrated in vacuo and the residue was purified by column chromatography with 1:9 MeOH-CHCl₃ to give **15** (3.52 g, 92% from **14**) as colorless needles: mp 121–122 °C (from AcOEt) (lit.,⁵ mp 123 °C, 47% yield); $R_f = 0.14$ (A); ¹H NMR δ = 2.00 (3H, s, NAc), 2.15, 2.90 (1H each, 2br s, HO-5,6), 3.36 (3H, s, MeO-1), 3.69 (1H, dd, $J_{6,6'} = 11.5$, $J_{5,6'} = 5.1$ Hz, H'-6), 3.83 (1H, dd, $J_{5,6} = 2.9$ Hz, H-6), 4.02 (1H, ddd, $J_{4,5} = 9.3$ Hz, H-5), 4.08 (1H, dd, $J_{3,4} = 6.4$, $J_{2,3} = 0.9$ Hz, H-3), 4.20 (1H, dd, H-4), 4.50 (1H, d, $J_{2,NH} = 7.9$, $J_{1,2} = 0$ Hz, H-2), 4.62, 4.92 (1H each, 2d, $^2J = 11.9$ Hz, CH₂O-3), 4.80 (1H, s, H-1), 5.68 (1H, d, HN-2), 7.32 [1H, m, Ph(*p*)], 7.34–7.36 [4H, t, Ph(*o,m*)]; ¹³C NMR δ = 23.21 (CH₃CO), 55.52 (MeO-1), 59.50 (C-2), 64.14 (C-6), 70.62 (C-5), 71.82 (CH₂O-3), 79.83 (C-4), 82.63 (C-3), 107.90 (C-1), 128.25 [Ph(*p*)], 128.25 [Ph(*o*)], 128.75 [Ph(*m*)], 137.08 [Ph(*ipso*)], 169.61 (CH₃CO).

Methyl 2-acetamido-5,6-anhydro-3-*O*-benzyl-2-deoxy-β-D-glucofuranoside (16).

By use of the same procedures described for **8** from **7**, compound **15** (2.90 g, 8.91 mmol) was treated with triphenylphosphine (2.83 g, 10.8 mmol) and DEAD (40% in toluene, 4.30 mL, 10.8 mmol) in toluene (60 mL) to give **16** (2.38 g, 87%) as colorless needles: mp 209–210 °C (from AcOEt-hexane); $R_f = 0.36$ (A); ¹H NMR δ = 1.97 (3H, s, NAc), 2.73 (1H, dd, $J_{6,6'} = 5.0$, $J_{5,6'} = 2.6$ Hz, H'-6), 2.90 (1H, dd, $J_{5,6} = 4.1$ Hz, H-6), 3.41 (ddt, 1H, $J_{4,5} = 6.7$ Hz, H-5), 3.41 (3H, s, MeO-1), 3.84 (1H, t, $J_{3,4} = 6.5$, H-4), 4.23 (dd, $J_{2,3} = 2.1$ Hz, H-3), 4.40 (dt, 1H, $J_{2,NH} = 7.6$, $J_{1,2} = 1.2$ Hz, H-2), 4.71, 4.81 (1H each, 2d, $^2J = 12.3$ Hz, CH₂O-3), 4.83 (1H, d, H-1), 5.53 (1H, d, HN-2), 7.27 [1H, t, $J_{m,p} = 7.4$ Hz, Ph(*p*)], 7.34 [2H, t, $J_{o,m} = 7.4$ Hz, Ph(*m*)], 7.39 [2H, d, Ph(*o*)]; ¹³C NMR δ = 23.24 (CH₃CO), 55.79 (MeO-1), 59.12 (C-2), 45.66 (C-6), 49.78 (C-5),

55.69 (MeO-1), 60.55 (C-2), 72.02 (CH₂O-3), 81.94 (C-4), 82.68 (C-3), 107.84 (C-1), 127.69 [Ph(*p*)], 127.79 [Ph(*o*)], 128.36 [Ph(*m*)], 137.78 [Ph(*ipso*)], 169.60 (CH₃CO). Anal. Calcd for C₁₆H₂₁NO₅: C, 62.53; H, 6.89. Found: C, 62.62; H, 6.93.

Methyl 2-acetamido-3,6-di-*O*-benzyl-2-deoxy-β-D-glucofuranoside (17a) and its 3,5-di-*O*-benzyl analog (17b).

A. From 16. By use of the same procedures described for **9a** from **8**, compound **16** (1.70 g, 5.53 mmol) was treated with benzyl alcohol (2.0 mL, 19.4 mmol) and sodium hydride (60% in mineral oil, 580 mg, 14.5 mmol) in DME (10 mL) to give **17a** (1.88 g, 82%).

B. From 15. To a solution of **15** (1.84 g, 5.65 mmol) in toluene (60 ml) was added dibutyltin oxide (1.72 g, 6.91 mmol) and then the suspension was refluxed under Dean-Stark trap for 15 h. After removal of the trap, benzyl bromide (1.35 mL, 11.4 mmol) and tetrabutylammonium iodide (1.05 g, 2.84 mmol) were added and the mixture was refluxed for 22 h. The mixture was evaporated in vacuo and the residue was separated by column chromatography on silica gel to give **17a** (1.70 g, 72%) and **17b** (430 mg, 18%).

17a: Colorless needles; mp 103–105 °C (from AcOEt-hexane); $R_f = 0.42$ (*A*); $[\alpha]_D^{26} -122.6$ (*c* 1.04, CHCl₃); ¹H NMR δ = 1.98 (3H, s, NAc), 2.92 (1H, d, $J_{5,OH} = 3.5$ Hz, HO-5), 3.32 (3H, s, MeO-1), 3.63 (1H, dd, $J_{6,6'} = 10.3$, $J_{5,6'} = 5.3$ Hz, H'-6), 3.70 (1H, dd, $J_{5,6} = 3.1$ Hz, H-6), 4.04 (1H, dd, $J_{3,4} = 6.2$, $J_{2,3} = 0.9$ Hz, H-3), 4.14 (ddt, 1H, $J_{4,5} = 8.8$ Hz, H-5), 4.23 (dd, 1H, H-4), 4.47 (dd, 1H, $J_{2,NH} = 7.6$, $J_{1,2} = 0$ Hz, H-2), 4.54, 4.59 (1H each, 2d, $^2J = 12.3$ Hz, CH₂O-6), 4.59, 4.87 (1H each, 2d, $^2J = 12.3$ Hz, CH₂O-3), 4.77 (1H, s, H-1), 5.72 (1H, d, HN-2), 7.26–7.36 (10H, m, Ph). Anal. Calcd for C₂₃H₂₉NO₆: C, 66.49; H, 7.04. Found: C, 66.60; H, 6.99.

17b: Colorless syrup; $R_f = 0.30$ (*A*); ¹H NMR δ = 1.99 (3H, s, NAc), 3.05 (1H, br s, HO-6), 3.40 (3H, s, MeO-1), 3.80 (1H, d, $J_{6,6'} = 12.0$, $J_{5,6'} = 3.0$ Hz, H'-6), 3.92 (1H, dd, $J_{5,6} = 3.5$ Hz, H-6), 3.99 (1H, dt, $J_{4,5} = 8.8$ Hz, H-5), 4.03 (1H, dd, $J_{3,4} = 5.0$, $J_{2,3} = 0.9$ Hz, H-3), 4.28 (dd, 1H, H-4), 4.46, 4.52 (1H each, 2d, $^2J = 11.2$ Hz, CH₂O-5), 4.50 (1H, d, $J_{2,NH} = 7.6$, $J_{1,2} = 0$ Hz, H-2), 4.59, 4.88 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-3), 4.84 (1H, s, H-1), 5.58 (d, 1H, HN-2), 7.26–7.36 (10H, m, Ph). Anal. Calcd for C₂₃H₂₉NO₆: C, 66.49; H, 7.04. Found: C, 66.68; H, 7.01.

Methyl 2-acetamido-3,6-di-*O*-benzyl-2-deoxy-β-D-xyllo-hexofuranosid-5-ulose (18).

A. Oxidation with oxalyl chloride-DMSO. By use of the same procedures described for **10** from **9a**, compound **17a** (1.54 g, 3.71 mmol) was treated with oxalyl chloride (0.960 mL, 11.2 mmol) and DMSO (1.60 mL, 22.5 mmol) in CH₂Cl₂ (20 mL) to give **18** (1.44 g, 94%) as a colorless syrup; $R_f = 0.37$ (*A*); ¹H NMR δ = 1.99 (1H, s, NAc), 3.44 (3H, s, MeO-1), 4.28 (1H, d, $J_{3,4} = 6.2$, $J_{2,3} = 0$ Hz, H-3), 4.31, 4.37 (1H

each, 2d, $J_{6,6'} = 17.9$ Hz, H₂-6), 4.33, 4.49 (1H each, 2d, $^2J = 11.7$ Hz, CH₂O-6), 4.46 (1H, d, $J_{2,\text{NH}} = 7.3$, $J_{1,2} = 0$ Hz, H-2), 4.53, 4.77 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-3), 4.84 (1H, d, H-4), 4.95 (1H, s, H-1), 5.70 (1H, d, HN-2), 7.22–7.38 (10H, m, Ph); ¹³C NMR $\delta = 23.10$ (CH₃CO), 56.07 (MeO-1), 58.92 (C-2), 71.94 (CH₂O-3), 73.19 (CH₂O-6), 74.23 (C-6), 83.28 (C-3), 85.89 (C-4), 109.33 (C-1), 127.78 and 127.83 [Ph(*p*)], 127.86 and 128.09 [Ph(*o*)], 128.32 and 128.37 [Ph(*m*)], 137.11 and 137.36 [Ph(*ipso*)], 169.91 (CH₃CO), 205.11 (C-5). Anal. Calcd for C₂₃H₂₇NO₆: C, 66.81; H, 6.58. Found: C, 66.54; H, 6.61.

B. Oxidation with PCC. To a suspension of PCC (1.38 g, 6.40 mmol) and finely powdered MS3A (2.0 g) in dry CH₂Cl₂ (20 mL) was added a solution of **17a** (1.10 g, 2.65 mmol) in dry CH₂Cl₂ (5 mL) at 0 °C. The mixture was stirred at rt for 6 h and then 2-propanol (5.0 mL) was added at 0 °C. The mixture was stirred for 30 min, diluted with Et₂O, and filtered. The filtrate was evaporated in vacuo and the residue was purified by column chromatography to give **18** (930 mg, 85%).

Methyl (5*R*)- and (5*S*)-2-acetamido-3,6-di-*O*-benzyl-2-deoxy-5-*C*-dimethoxyphosphoryl- β -D-xylohexofuranosides (**19**).

By use of the same procedures described for **11** from **10**, compound **18** (1.37 g, 3.31 mmol) was treated with dimethyl phosphonate (15 mL) and DBU (0.75 mL, 5.0 mmol) to give (5*R*)-**19** (1.20 g, 69%) and (5*S*)-**19** (430 mg, 25%).

(5*R*)-**19**: Colorless prisms; mp 144–145 °C (from AcOEt); $R_f = 0.35$ (*B*); $[\alpha]_{\text{D}}^{26} -75.3$ (*c* 1.04, CHCl₃); ¹H NMR $\delta = 2.01$ (3H, s, NAc), 3.39 (3H, s, MeO-1), 3.64, 3.68 (3H each, 2d, $J_{\text{POMe}} = 10.7$ Hz, POMe), 3.75 (1H, dd, $J_{6',\text{P}} = 12.5$, $J_{6,6'} = 8.9$ Hz H'-6), 3.90 (1H, dd, $J_{6,\text{P}} = 26.2$ Hz, H-6), 4.28 (1H, d, $J_{3,4} = 4.9$, $J_{2,3} = 0$ Hz, H-3), 4.48 (1H, d, $J_{2,\text{NH}} = 7.4$, $J_{1,2} = 0$ Hz, H-2), 4.56, 4.90 (1H each, 2d, $^2J = 11.0$ Hz, CH₂O-3), 4.59 (1H, d, $J_{4,\text{P}} = 0$ Hz, H-4), 4.60, 4.63 (1H each, 2d, $^2J = 11.9$ Hz, CH₂O-6), 4.86 (1H, d, $^5J_{1,\text{P}} = 1.0$ Hz, H-1), 4.99 (1H, s, HO-5), 5.75 (1H, d, HN-2), 7.26–7.39 (10H, m, Ph); ³¹P NMR $\delta = 26.21$. Anal. Calcd for C₂₅H₃₄NO₉P: C, 57.36; H, 6.55. Found: C, 57.47; H, 6.52.

(5*S*)-**19**: Colorless syrup; $R_f = 0.26$ (*B*); $[\alpha]_{\text{D}}^{26} -74.0$ (*c* 3.47, CHCl₃); ¹H NMR $\delta = 2.01$ (3H, s, NAc), 3.44 (3H, s, MeO-1), 3.55 (2H, dd, $J_{6',\text{P}} = 25.9$, $J_{6,6'} = 9.2$ Hz H'-6), 3.77, 3.85 (3H each, 2d, $J_{\text{P,H}} = 10.5$ Hz, MeOP), 3.79 (2H, dd, $J_{6,\text{P}} = 10.9$ Hz, H-6), 4.05 (1H, d, $J_{3,4} = 4.9$, $J_{2,3} = 0$ Hz, H-3), 4.26, 4.42 (1H each, 2d, $^2J = 11.9$ Hz, CH₂O-6), 4.29 (1H, br s, HO-5), 4.30, 4.75 (1H each, 2d, $^2J = 11.6$ Hz, CH₂O-3), 4.45 (1H, d, $J_{2,\text{NH}} = 7.3$, $^5J_{2,\text{P}} = 1.2$, $J_{1,2} = 0$ Hz, H-2), 4.66 (1H, t, $J_{4,\text{P}} = 4.6$ Hz, H-4), 4.95 (1H, s, H-1), 6.32 (1H, d, HN-2), 7.24–7.35 (10H, m, Ph); ³¹P NMR $\delta = 24.84$.

Methyl (5*R*)- and (5*S*)-2-acetamido-3,6-di-*O*-benzyl-2-deoxy-5-*C*-dimethoxyphosphoryl-5-*O*-methoxalyl- α -D-xylohexofuranosides (**20**).

By use of the same procedures described for **12** from **11**, compound **19** (74:26 diastereomeric mixture,

660 mg, 1.26 mmol) was treated with methoxalyl chloride (0.240 mL, 2.51 mmol) and DMAP (433 mg, 3.54 mmol) to give an inseparable diastereomeric mixture (74:26) of **20** (654 mg, 85%) as a colorless syrup: $R_f = 0.40$ (*B*).

(5*R*)-**20**: $^1\text{H NMR } \delta = 1.96$ (3H, s, NAc), 3.32 (3H, s, MeO-1), 3.70–3.82 (2H, m, H-6, 6'), 3.73, 3.79 (3H each, 2d, $J_{\text{POMe}} = 11.2$ Hz, POMe), 3.81 (3H, s, COOMe), 3.97 (1H, dd, $J_{3,4} = 5.3$, $J_{2,3} = 1.2$ Hz, H-3), 4.48 (1H, dd, $J_{2,\text{NH}} = 7.9$, $J_{1,2} = 0$ Hz, H-2), 4.51, 4.73 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-3 or 6), 4.54, 4.75 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-3 or 6), 4.85 (1H, d, $^5J_{1,2} = 1.1$ Hz, H-1), 5.25 (1H, dd, $J_{4,\text{P}} = 8.8$ Hz, H-4), 5.97 (1H, d, HN-2), 7.25–7.38 (10H, m, Ph). Anal. Calcd for C₂₅H₃₄NO₉P: C, 57.36; H, 6.55. Found: C, 57.47; H, 6.52.

(5*S*)-**20**: $^1\text{H NMR } \delta = 1.99$ (3H, s, NAc), 3.25 (3H, s, MeO-1), 3.70–3.82 (2H, m, H-6, 6'), 3.70, 3.76 (3H each, 2d, $J_{\text{POMe}} = 11.2$ Hz, POMe), 3.87 (3H, s, COOMe), 4.07, 4.64 (1H each, 2d, $^2J = 10.9$ Hz, CH₂O-3 or 6), 4.09, 4.68 (1H each, 2d, $^2J = 10.9$ Hz, CH₂O-3 or 6), 4.13 (1H, dd, $J_{3,4} = 5.0$, $J_{2,3} = 1.0$ Hz, H-3), 4.45 (1H, dd, $J_{2,\text{NH}} = 9.4$, $J_{1,2} = 0$ Hz, H-2), 4.83 (1H, s, H-1), 5.13 (1H, dd, $J_{4,\text{P}} = 3.5$ Hz, H-4), 5.92 (1H, d, HN-2), 7.25–7.38 (10H, m, Ph).

Methyl 2-acetamido-3,6-di-*O*-benzyl-2,5-dideoxy-5-dimethoxyphosphoryl- β -D-glucofuranoside (**21a**) and its α -L-idofuranoside analog (**21b**).

To a solution of **20** (695 mg, 1.14 mmol) in toluene (5 mL), a solution of AIBN (101 mg, 0.625 mmol) and tributyltin hydride (0.610 mL, 2.27 mmol) in dry toluene (3 mL) was dropwise added at 90 °C under argon. The mixture was stirred at the same temperature for 6 h and then concentrated in vacuo. The residue was separated by column chromatography with 1:9 EtOH-AcOEt into three fractions A–C.

Fraction A [$R_f = 0.68$ (*B*)] gave a pale yellow syrup which mainly consisted of **18** (53.5 mg, 12%).

Fraction B [$R_f = 0.30$ (*B*)] gave **21a** (249 mg, 43%) as colorless needles: mp 113–115 °C (from AcOEt); $[\alpha]_{\text{D}}^{29} -52.0$ (*c* 1.07, CHCl₃); $^1\text{H NMR } \delta = 2.00$ (3H, s, NAc), 2.89 (1H, dddd, $J_{5,\text{P}} = 19.5$, $J_{4,5} = 9.4$, $J_{5,6'} = 5.3$, $J_{5,6} = 3.2$ Hz, H-5), 3.35 (3H, s, MeO-1), 3.58, 3.64 (3H each, 2d, $J_{\text{POMe}} = 10.9$ Hz, POMe), 3.90–3.96 (2H, m, H,H'-6), 3.96 (d, 1H, $J_{3,4} = 4.2$, $J_{2,3} = 0$ Hz, H-3), 4.43 (1H, dd, $J_{2,\text{NH}} = 7.6$, $J_{1,2} = 1.2$ Hz, H-2), 4.50, 4.84 (1H each, 2d, $^2J = 11.7$ Hz, CH₂O-3), 4.54, 4.58 (1H each, 2d, $^2J = 12.0$ Hz, CH₂O-6), 4.55 (1H, ddd, $J_{4,\text{P}} = 7.3$ Hz, H-4), 4.79 (1H, d, $^5J_{1,\text{P}} = 1.2$ Hz, H-1), 5.94 (1H, d, HN-2), 7.25–7.37 (10H, m, Ph); $^{13}\text{C NMR } \delta = 23.19$ (CH₃CO), 37.50 (d, $^1J_{5,\text{P}} = 136.9$ Hz, C-5), 52.21 (d, $^2J_{\text{C,P}} = 6.7$ Hz, POMe), 52.80 (d, $^2J_{\text{C,P}} = 6.2$ Hz, POMe), 55.79 (MeO-1), 59.12 (C-2), 66.96 (d, $^2J_{6,\text{P}} = 8.4$ Hz, C-6), 71.61 (CH₂O-3), 73.35 (CH₂O-6), 77.82 (d, $^2J_{4,\text{P}} = 5.6$ Hz, C-4), 82.30 (d, $^3J_{3,\text{P}} = 2.3$ Hz, C-3), 108.33 (C-1), 127.44 and 127.48 [Ph(*p*)], 127.60 and 127.83 [Ph(*o*)], 128.17 and 128.22 [Ph(*m*)], 138.02 and 138.19 [Ph(*ipso*)], 169.75 (CH₃CO); $^{31}\text{P NMR } \delta = 32.25$. Anal. Calcd for C₂₅H₃₄NO₈P: C, 59.16; H, 6.75. Found: C, 59.04; H, 6.78.

Fraction C [$R_f = 0.25$ (*B*)] gave **21b** (105 mg, 18%) as a colorless syrup; $[\alpha]_D^{29} -92.6$ (c 2.79, CHCl_3); ^1H NMR $\delta = 2.01$ (3H, s, NAc), 2.70 (1H, dddd, $J_{5,\text{P}} = 18.2$, $J_{4,5} = 10.6$, $J_{5,6'} = 3.5$, $J_{5,6} = 2.9$ Hz, H-5), 3.31 (1H, ddd, $J_{6',\text{P}} = 31.7$, $J_{6,6'} = 9.7$ Hz, H'-6), 3.40 (3H, s, MeO-1), 3.68 (1H, d, $J_{3,4} = 4.4$, $^4J_{3,\text{P}} = 1.2$, $J_{2,3} = 0$ Hz, H-3), 3.69 (1H, ddd, $J_{6,\text{P}} = 10.7$ Hz, H-6), 3.70, 3.75 (3H each, 2d, $J_{\text{POMe}} = 10.9$ Hz, POMe), 4.15, 4.29 (1H each, 2d, $^2J = 12.0$ Hz, CH_2O -6), 4.40, 4.80 (1H each, 2d, $^2J = 11.7$ Hz, CH_2O -3), 4.41 (1H, dd, $J_{2,\text{NH}} = 7.3$, $^5J_{2,\text{P}} = 1.5$, $J_{1,2} = 0$ Hz, H-2), 4.48 (1H, ddd, $J_{4,\text{P}} = 7.0$ Hz, H-4), 4.89 (1H, s, H-1), 6.19 (1H, d, HN-2), 7.20–7.33 (10H, m, Ph); ^{13}C NMR $\delta = 23.10$ (CH_3CO), 38.43 (d, $^1J_{5,\text{P}} = 142.5$ Hz, C-5), 52.22 (d, $^2J_{\text{C},\text{P}} = 7.3$ Hz, POMe), 52.80 (d, $^2J_{\text{C},\text{P}} = 6.2$ Hz, POMe), 55.73 (MeO-1), 58.76 (C-2), 66.36 (d, $^2J_{6,\text{P}} = 7.3$ Hz C-6), 70.84 (CH_2O -3), 73.07 (CH_2O -6), 78.35 (d, $^2J_{4,\text{P}} = 3.9$ Hz, C-4), 80.44 (d, $^3J_{3,\text{P}} = 11.8$ Hz, C-3), 108.38 (C-1), 127.66 and 127.75 [$\text{Ph}(p)$], 127.77 and 128.25 [$\text{Ph}(o)$], 128.25 and 128.60 [$\text{Ph}(m)$], 137.34 and 137.74 [$\text{Ph}(ipso)$], 169.89 (CH_3CO); ^{31}P NMR $\delta = 33.29$. Anal. Calcd for $\text{C}_{25}\text{H}_{34}\text{NO}_8\text{P}$: C, 59.16; H, 6.75. Found: C, 58.98; H, 6.72.

2-Acetamido-1,3,4,6-tetra-*O*-acetyl-2,5-dideoxy-5-methoxyphosphoryl-D-glucopyranoses (**25a–d**).

To a solution of **21a** (103 mg, 0.203 mmol) in dry toluene (2.0 mL) was added, with stirring, a solution of 0.34 M SDMA in toluene (2.5 mL, 0.85 mmol) in small portions at -5 °C under argon. The stirring was continued at this temperature for 1.5 h and diluted with benzene. Then, water (0.10 mL) was added to decompose excess SDMA and the mixture was centrifuged. The precipitate was extracted with several portions of benzene. The organic layers were combined and evaporated in vacuo, giving the 5-deoxy-5-phosphino derivative (**22**) as a colorless syrup: $R_f = 0.44$ (*B*).

This syrup was immediately treated with 1:1 2-propanol–0.5 M hydrochloric acid (3.0 mL) at 90 °C for 1 h under argon. After cooling, the mixture was evaporated in vacuo. The residue was dissolved in MeOH (1.0 mL), treated with 30% hydrogen peroxide (0.6 mL, 5.9 mmol) at rt for 12 h and then concentrated in vacuo. The residue was dissolved in MeOH (1.0 mL), treated with propylene oxide (0.5 mL) at rt for 2 h, and evaporated in vacuo to give crude 5-deoxy-5-hydroxyphosphoryl-D-glucopyranose derivatives (**23**) as a colorless syrup.

This was dissolved in dry pyridine (1.5 mL), and acetic anhydride (0.6 mL, 6.3 mmol) was added at 0 °C. The mixture was stirred at rt for 15 h, diluted with a small amount of cold water, and concentrated in vacuo. The residue was dissolved in methanol and passed through a column of Amberlite IR-120(H^+) (10 mL). The eluent was evaporated in vacuo and the residue was methylated with (trimethylsilyl)diazomethane (2M in ether, 0.40 mL, 0.80 mmol) in dry CH_2Cl_2 (1.0 mL) at rt for 3 h. After evaporation of the solvent, the residue was purified by column chromatography with 1:1 EtOH–AcOEt to give an inseparable mixture of the 2-acetamido-3,6-*O*-dibenzyl-2,5-dideoxy-5-methoxyphosphoryl derivatives (**24**) as a colorless syrup: $R_f = 0.30$ – 0.25 (*B*).

The compounds **24** dissolved in 1:1 EtOH-AcOEt (2.0 mL) was hydrogenated in the presence of 20% Pd(OH)₂-C (3.0 mg) at rt under atmospheric pressure of hydrogen. After 24 h, the catalyst was filtered off and the filtrate was evaporated in vacuo. The residue was acetylated again with dry pyridine (1.0 mL) and acetic anhydride (0.20 mL). The mixture was evaporated in vacuo and the residue was separated by column chromatography with a gradient eluent of AcOEt to 1:9 EtOH-AcOEt into two fractions.

The faster-eluting fraction [$R_f = 0.36\text{--}0.32$ (*B*)] gave a colorless syrup (17.5 mg), which consisted of the 5-[(*R*)-methoxyphosphoryl]- α -D-glucopyranose (**25a**) (7.5% from **21a**) and its 5-[(*S*)-P]- α -isomer (**25c**) (11.6%), the ratio being estimated by ¹H NMR: ¹H and ³¹P NMR, see Table 1. HRMS (FAB): *m/z* calcd for C₁₇H₂₇NO₁₁P [M + H]⁺ 452.1322, found 452.1333.

The slower-eluting fraction [$R_f = 0.34\text{--}0.30$ (*B*)] gave a colorless syrup (11.2 mg) which consisted of **25c** (7.2% from **21a**), 5-[(*R*)-P]- β -isomer (**25b**) (2.7%), and its 5-[(*S*)-P]- β -isomer (**25d**) (2.3%), the ratio being estimated by ¹H NMR: ¹H and ³¹P NMR, see Table 1.

2-Acetamido-1,3,4,6-tetra-*O*-acetyl-2,5-dideoxy-5-methoxyphosphoryl-L-idopyranoses (**29a–d**).

The procedures similar to those for preparation of compounds **25** from **21a** were employed. Thus, compound **13b** (101 mg, 0.206 mmol) were converted into the diastomeric L-idopyranoses (**29**) via intermediates **26**, **27**, and **28**. The crude product **29** was separated by column chromatography into two fractions.

The faster-eluting fraction [$R_f = 0.26\text{--}0.22$ (*B*)] gave a colorless syrup (10.2 mg), which consisted of the 5-[(*R*)-methoxyphosphoryl]- β -L-idopyranose (**29a**) (3.4% from **13a**), its 5-[(*R*)-P]- α -isomer (**29b**) (4.3%), and 5-[(*S*)-P]- β -isomer (**29c**) (3.2%), the ratio being estimated by ¹H NMR: ¹H and ³¹P NMR, see Table 1. HRMS (FAB): *m/z* calcd for C₁₇H₂₇NO₁₁P [M + H]⁺ 452.1322, found 452.1311.

The slower-eluting fraction [$R_f = 0.24\text{--}0.20$ (*B*)] gave a colorless syrup (8.5 mg) which consisted of **29b** (4.0% from **13b**), its 5-[(*S*)-P]- β -isomer (**29c**) (2.2%), and 5-[(*S*)-P]- α -isomer (**29d**) (3.0%), the ratio being estimated by ¹H NMR: ¹H and ³¹P NMR, see Table 1.

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