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Chemical Synthesis of Polysaccharides XI.† Ring-Opening Polymerization of 1,6-Anhydro-2-*O*-(*p*-Substituted Benzoyl) Deoxysugar Derivatives

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ABSTRACT: The present paper is concerned with the applicability of the neighboring group participation of a 2-*O*-(*p*-substituted benzoyl) group to the stereoregulation of the ring-opening polymerization of 1,6-anhydro deoxysugar derivatives. 1,6-Anhydro-2-*O*-(*p*-substituted benzoyl)-3,4-dideoxy-β-D-*erythro*-hexopyranoses (**5a**—**d**) were polymerized in dichloromethane at different temperatures ranging from −60 and −20°C with phosphorus pentafluoride as an initiator. 1,6-Anhydro-2-*O*-benzoyl-3-*O*-benzyl-4-deoxy-β-D-*xylo*-hexopyranose (**7a**) and its 2-*O*-(*p*-bromobenzoyl) homolog (**7b**) were also polymerized under similar conditions. ^{13}C NMR analysis revealed that all the polymers were composed of both the respective (1→6)-α- and (1→6)-β-linked structural units. Their proportions varied depending on the *p*-substituents as well as the reaction conditions: An electron-withdrawing *p*-substituent on the 2-*O*-benzoyl aromatic ring reduced the β-unit content of the polymer, although it increased the polymer yield. The presence of a 3-*O*-benzyl group was favorable for the formation of (1→6)-β-linked structural units. On the basis of these results, factors disturbing the configurational regularity of the anomeric carbons were discussed.

KEY WORDS Anhydro Sugar Derivatives / Neighboring Group Participation / Synthetic Polysaccharides / Ring-Opening Polymerization / Stereoregulation / Substituent Effect /

A variety of homo- and heteropolysaccharides have been synthesized not only as model compounds for elucidating sophisticated functions of naturally occurring polysaccharides but also as novel bioactive or biocompatible specialty polymers.[1-4] Among the methodologies used for the synthesis of polysaccharides, cationic ring-opening polymerization of anhydro sugar derivatives is most useful for synthesizing homopolysaccharides with high molecular weights. Above all, the synthetic procedures for (1→6)-α-linked polysaccharides by ring-opening polymerization of 1,6-anhydro sugar derivatives have been well established.

In nature, there are bioactive oligo- and polysaccharides having a (1→6)-β-linked backbone such as ε-galactan and psutulan.[5,6] In order to broaden the scope of the chemical synthesis of polysaccharides by ring-opening polymerization of anhydro sugar derivatives, it is highly desirable to develop effective and widely applicable methods for synthesizing stereoregular (1→6)-β-linked polysaccharides from 1,6-anhydro sugar derivatives.

Previously, we found unexpectedly that 1,6-anhydro-2,3-di-*O*-benzyl-4-deoxy-β-DL-*ribo*-hexopyranose (**1**) underwent ring-opening polymerization to give 4-deoxy-(1→6)-β-DL-*ribo*-hexopyranan (**2b**) after deprotection.[7,8]

† Part X. See ref 24.

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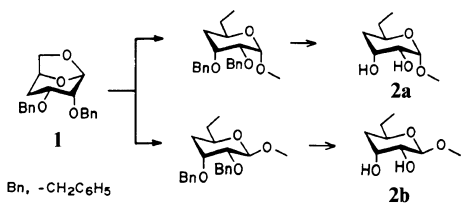
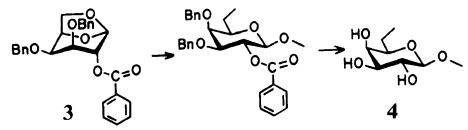
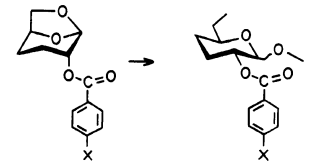


The monomer **1** gave the (1→6)-β-linked polysaccharide **2b**, when it was polymerized in a dilute solution at −60°C, whereas the same monomer afforded the (1→6)-α-linked polysaccharide **2a** when its polymerization was carried out in a concentrated solution at −90°C and terminated in a short time.[7] It was proposed that **2b** was produced by thermodynamic control, whereas **2a** was produced by kinetic control.[9-11] However, this technique cannot generally be applied to the synthesis of other (1→6)-β-linked polysaccharides.

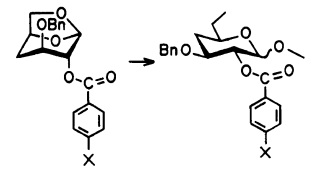
A more universally applicable approach to the synthesis of (1→6)-β-linked polysaccharide is to utilize a neighboring group participation. Thus, (1→6)-β-D-galactopyranan (**4**) was successfully synthesized by cationic ring-opening polymerization of 1,6-anhydro-2-*O*-benzoyl-3,4-di-*O*-benzyl-β-D-galactopyranose (**3**) followed by deprotection, although both the yield and the degree of polymerization were low.[12,13]



The present investigation was undertaken to check the applicability of this approach to the synthesis of stereoregular (1→6)-β-linked polysaccharides by ring-opening polymerization of 1,6-anhydro deoxysugar derivatives. Thus, 1,6-anhydro-2-*O*-(*p*-substituted benzoyl)-3,4-dideoxy-β-D-*erythro*-hexopyranoses (**5a—d**) were polymerized at different temperatures, and the structure of the resulting polymers (**6a—d**) was examined by ^{13}C NMR analysis. Polymerization of 1,6-anhydro-2-*O*-benzoyl-3-*O*-benzyl-4-deoxy-β-D-*xylo*-hexopyranose (**7a**) and its 2-*O*-(*p*-bromobenzoyl) homolog (**7b**) were also investigated in order to evaluate the additional effect of the 3-*O*-benzyl group on the stereochemical course of the propagation.



5a: X=CH_3 **6a**: X=CH_2
5b: X=H **6b**: X=H
5c: X=Br **6c**: X=Br
5d: X=CF_3 **6d**: X=CF_3



7a: X=H **8a**: X=H
7b: X=Br **8b**: X=Br

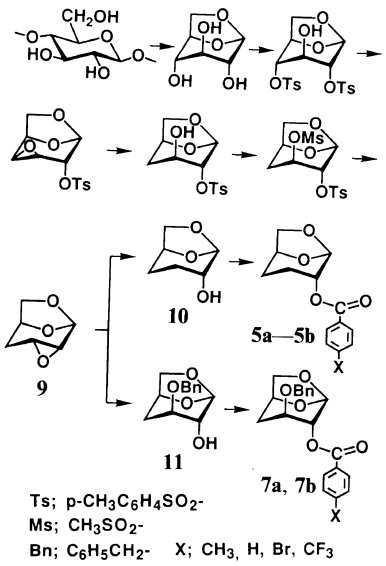
EXPERIMENTAL

Syntheses of Monomers

All the monomers **5a—d**, **7a** and **7b** were synthesized starting from cellulose as illustrated in Scheme 1. The common precursor, 1,6:2,3-dianhydro-4-deoxy-β-D-*ribo*-hexopyranose (**9**) was prepared according to the procedures described by Černý *et al.*[14-17] with some modifications.

Preparation of 1,6-Anhydro-3,4-dideoxy-β-D-erythro-hexopyranose (**10**)

A solution of **9** (1.28 g, 10 mmol) in diethyl ether (25 ml) was slowly added to a solution of lithium aluminum hydride (0.83 g, 21 mmol) in diethyl ether (26 ml). The mixture was stirred at room temperature for 3 h. Diethyl ether (20 ml) saturated with water, 20% sodium hydroxide aqueous solution (2.4 ml), and water (10 ml) were successively added to the reaction mixture. The resulting mixture was stirred for



Scheme 1. Synthetic routes for 1,6-anhydro-3,4-dideoxy-β-D-*erythro*-hexopyranose derivatives (**5a**—**d**) and 1,6-anhydro-4-deoxy-β-D-*xylo*-hexoypyranose derivatives (**7a**, **b**).

15 min to give a white precipitate. It was removed by filtration, and the filtrate was dried over anhydrous magnesium sulfate. The solvent was removed by distillation, and the colorless residue was recrystallized from diethyl ether. Yield of **10**, 62%. ^{13}C NMR ($CDCl_3$), δ 102.0 (C-1), 72.2 (C-5), 66.8 (C-2), 24.8 (C-4), 23.2 ppm (C-3).

*Preparation of 1,6-Anhydro-2-O-(p-bromobenzoyl)-3,4-dideoxy-β-*D*-erythro-hexopyranose* (**5c**)

A solution of *p*-bromobenzoyl chloride (4.4 g, 20 mmol) in chloroform (20 ml) was slowly added to a solution of **10** in triethylamine (0.55 g, 4.2 mmol). The mixture was stirred at 50°C for 1 h. TLC showed complete disappearance of **10**. Water (5 ml) was added to the solution, and the reaction mixture was stirred at room temperature for 2 h. The chloroform layer was separated from the aqueous layer, and the aqueous layer was extracted with three 20 ml portions of chloroform. The combined chloroform extracts were washed with a saturated aqueous solution of sodium bicarbonate and water successively, and dried over anhydrous magnesium sulfate overnight. After filtration, chloroform was removed by rotary evaporation. The brown oily residue was recrystallized from ethanol. Yield of **5c**, 55%; mp 63—64°C; $[\alpha]_D^{25}$, −1.4° (*c* 1.0, $CHCl_3$); ^{13}C NMR ($CDCl_3$), δ 165.0 (C=O), 131.6 (phenyl, *meta*), 131.2 (phenyl, *ortho*), 128.9 (phenyl, *ipso*), 128.1 (phenyl, *para*), 99.5 (C-1), 73.0 (C-2), 68.8 (C-5), 66.9 (C-6), 25.2 (C-4), 21.0 ppm (C-3).

In a similar manner, the monomers **5a**, **5b**, and **5d** were prepared by the reactions of **10** with the corresponding benzoyl chlorides. **5a**: mp 58—59°C; $[\alpha]_D^{25}$, −3.6° (*c* 0.8, $CHCl_3$); ^{13}C NMR ($CDCl_3$), δ 165.9 (C=O), 143.7 (phenyl, *para*), 129.7 (phenyl, *meta*), 129.0 (phenyl, *ortho*), 127.3 (phenyl, *ipso*), 99.7 (C-1), 73.0 (C-2), 68.3 (C-5), 66.8 (C-6), 25.2 (C-4), 21.7 (CH_3), 21.0 ppm (C-3). **5b**: mp 79—81°C; $[\alpha]_D^{25}$, −6.9° (*c* 1.0, $CHCl_3$); ^{13}C NMR ($CDCl_3$), δ 165.5 (C=O), 132.8 (phenyl, *ipso*), 129.5 (phenyl, *ortho*), 128.1 (phenyl, *meta* and *para*), 99.5 (C-1), 73.0 (C-2), 68.4 (C-5), 66.8 (C-6), 25.2 (C-4), 21.0 ppm (C-3). **5d**: mp 104—105°C; $[\alpha]_D^{25}$, −4.2° (*c* 1.0, $CHCl_3$); ^{13}C NMR ($CDCl_3$, TMS), δ 164.4 (C=O), 134.4 (q, J_{CF}=35 Hz, phenyl, *para*), 133.2 (phenyl, *ipso*), 130.0 (phenyl, *ortho*), 125.2 (phenyl, *meta*), 123.4 (q, J_{CF}=270 Hz, CF_3), 99.4 (C-1), 73.0 (C-2), 69.1 (C-5), 66.8 (C-6), 25.2 (C-4), 21.0 ppm (C-3).

*Preparation of 1,6-Anhydro-3-O-benzyl-4-deoxy-β-*D*-xylo-hexopyranose* (**11**)

A solution of **9** (1.3 g, 10 mmol) in benzyl alcohol (5 ml, 50 mmol) was added to a solution of metallic sodium (0.7 g, 30 mmol) dissolved in benzyl alcohol (1 ml). The mixture was stirred at 100°C for 11 h. The solvent was removed by rotary evaporation to yield a viscous residue, which was purified by column chromatography (silica gel; eluent, ethyl acetate). The monobenzylated anhydro sugar derivative **11** was obtained as colorless crystals.

Yield, 31%; mp 72—73°C. ^{13}C NMR ($CDCl_3$), δ 138.2 (phenyl, *ipso*), 128.4 (phenyl, *meta*), 127.6 (phenyl, *para*), 127.4 (phenyl, *ortho*), 101.5 (C-1), 75.1 (C-3), 71.8 (C-5), 71.2 (benzyl CH_2), 68.0 (C-2), 67.3 (C-6), 30.7 ppm (C-4).

Preparation of 1,6-Anhydro-3-O-benzyl-2-O-(p-bromobenzoyl)-4-deoxy-β-D-xylo-hexopyranose (**7b**)

A solution of *p*-bromobenzoyl chloride (4.4 g, 20 mmol) in chloroform, (10 ml) was slowly added to a solution of **11** (0.72 g, 3.1 mmol) in triethylamine (10 ml). The mixture was heated at 50°C for 45 min. After the complete consumption of **11** was confirmed by TLC, a small amount of water was added to the reaction mixture. The mixture was stirred for 2 h at room temperature. The organic layer was separated from the aqueous layer. The aqueous layer was extracted with three 20 ml portions of chloroform. The combined chloroform extracts were washed with a saturated aqueous solution of sodium bicarbonate and water successively, and dried over anhydrous magnesium sulfate. Rotary evaporation of the solvent gave a viscous residue, which was purified by silica gel column chromatography (eluent, *n*-hexane–ethyl acetate = 5 : 2). The anhydro sugar derivative **7b** was obtained as colorless needles. Yield, 64%; mp 82—83°C; $[\alpha]_D^{25}$ +15.6° (*c* 1.0, $CHCl_3$). ^{13}C NMR ($CDCl_3$), δ 164.8 (C=O), 138.2 (benzyl, *ipso*), 131.8, 131.3, 128.4, 127.4 (arom.), 99.4 (C-1), 72.7 (C-2), 71.4 (C-3), 71.3 (benzyl, CH_2), 69.1 (C-5), 67.3 (C-6), 32.1 ppm (C-4).

In a similar manner, 1,6-Anhydro-2-*O*-benzoyl-3-*O*-benzyl-4-deoxy-β-D-*xylo*-hexopyranose (**7a**) was prepared by the reaction of **11** with benzoyl chloride. **7a**: mp 77—78°C; $[\alpha]_D^{25}$, −0.1° (*c* 0.7, $CHCl_3$); ^{13}C NMR ($CHCl_3$), δ 165.5 (C=O), 138.3 (benzyl, *ipso*), 133.3 (benzoyl, *ipso*), 129.8, 128.4, 127.4 (arom.), 99.4 (C-1), 72.8 (C-2), 71.4 (C-3), 71.2 (benzyl, CH_2), 68.7 (C-5), 67.2 (C-6), 32.1 ppm (C-4).

Polymerization

Polymerization was carried out in dichloromethane at different temperatures between −60 and −20°C by using a conventional high vacuum technique. Phosphorus pentafluoride as an initiator was generated by the thermal decomposition of *p*-chlorobenzene diazonium hexafluorophosphate. The polymerization was terminated by the addition of methanol. The polymer was purified by reprecipitation with dichloromethane and methanol as a solvent-precipitant pair, followed by freeze-drying from a benzene solution.

^{13}C NMR ($CDCl_3$) **6b**: δ 165.5 (C=O, α), 165.2 (C=O, β), 132.7 (phenyl, *ipso*), 130.2 (phenyl, *para*), 129.5 (phenyl, *ortho*), 128.2 (phenyl, *meta*), 102.7, 102.3 (C-1, β), 96.0 (C-1, α), 74.8, 74.3 (C-2, β), 71.3, 70.9 (C-2, α), 69.3 (C-6), 67.1 (C-5), 27.5 (C-4, β), 26.7 (C-4, α), 23.1 ppm (C-3).

6c: δ 165.0 (C=O, α), 164.7 (C=O, β), 131.8 (phenyl, *meta*), 131.2 (phenyl, *ortho*), 129.2 (phenyl, *ipso*), 128.2 (phenyl, *para*), 103.0, 102.4 (C-1, β), 96.0 (C-1, α), 74.8, 74.3 (C-2, β), 71.5, 71.1 (C-2, α), 69.3 (C-6), 67.2 (C-5), 27.4 (C-4, β), 26.7 (C-7, α), 23.0 ppm (C-3).

6d: δ 164.7 (C=O, α), 164.4 (C=O, β), 134.7 (J_{CF} = 35 Hz, phenyl, *para*), 133.7 (phenyl, *ipso*), 130.2 (phenyl, *ortho*), 125.6 (phenyl, *meta*), 123.8 (J_{CF} = 273 Hz, CF_3), 102.9, 102.5 (C-1, β), 96.2 (C-1, α), 71.8 (C-2, β), 71.5 (C-2, α), 69.4 (C-6), 67.4 (C-5), 27.5 (C-4, β), 26.6 (C-4, α), 23.1 ppm (C-3).

8a: δ 166.1 (C=O, α), 165.4 (C=O, β), 138.5 (benzyl, *ipso*, α), 138.1 (benzyl, *ipso*, β), 133.2 (benzoyl, *ipso*), 130.6—127.5 (phenyl), 102.9, 101.8, 101.5 (C-1, β), 97.2 (C-1, α), 76.1 (C-2, β), 75.0 (C-2, α), 72.8 (C-3), 71.8, 71.0 (benzyl CH_2), 69.1 (C-6), 66.6 (C-5), 33.3 ppm (C-4).

8b: δ 165.1 (C=O, α), 164.6 (C=O, β), 138.4, 138.0 (benzyl, *ipso*), 132.0—127.5 (phenyl), 103.1, 101.7, 101.4 (C-1, β), 97.2 (C-1, α), 75.9 (C-2, β), 75.1 (C-2, α), 72.7 (C-3), 71.8 (benzyl CH_2, β), 71.4 (benzyl CH_2, α), 69.3 (C-6), 66.8 (C-5), 33.3 ppm (C-4).

Characterization

^{13}C NMR spectra were recorded on a JEOL FX-270 spectrometer operating at 67.8 MHz on solutions in deuteriochloroform. Tetramethylsilane was used as the internal reference. Specific rotations were measured in chloroform at 25°C by a JASCO DIP 181 automatic polarimeter. Molecular weights of polymers were estimated by gel permeation chromatography (eluent chloroform, polystyrene standard).

RESULTS AND DISCUSSION

Polymerization of the anhydro sugar derivatives **5a—d**, **7a**, and **7b** was undertaken in dichloromethane at different temperatures between −60 and −20°C with phosphorus pentafluoride as an initiator. The results are summarized in Table I.

Figure 1 shows the ^{13}C NMR spectrum of the polymer (K-5) of **5c**. There are two groups of signals in the anomeric carbon region. The lower field signals were assigned to the anomeric carbon of the β-form unit and the higher field signal to that of the α-form unit, respectively. On the basis of the assignment, the β-unit content of the polymer can be estimated from the relative areas of these signals. The β-unit contents of other polymers were evaluated in a similar manner and collected in the 2nd column from the right in Table I. It is noteworthy that all the monomers

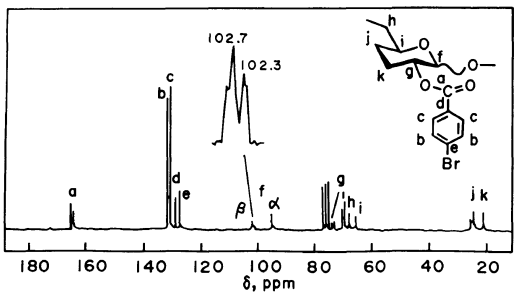


Figure 1. ^{13}C NMR spectrum of 2-*O*-(*p*-bromobenzoyl)-3,4-dideoxy-(1→6)-D-*erythro*-hexopyranan (solv., $CDCl_3$; 50°C; 25 MHz; tetramethylsilane).

Table I. Polymerization of 1,6-anhydro deoxysugar derivatives having a 2-*O*-(*p*-substituted benzoyl) group[a]

Entry No.	Monomer		$[M]_0$	Temp	Time	Yield[c]	M_n[d] $\times 10^{-3}$	β-Form[e]	$[\alpha]_D^{25}$[f]
	X[b]		mol l^{-1}	°C	h	%		%	
1	**5a**	CH_3	2.0	−40	96	2	3.5	(60)[g]	—
2	**5b**	H	2.0	−20	60	28	3.3	25	+62
3	**5b**	H	2.0	−60	120	8	2.8	54	—
4	**5c**	Br	1.2	−40	96	58	2.7	43	+36
5	**5c**	Br	2.0	−40	96	68	4.8	35	+35
6	**5c**	Br	2.0	−40	36	57	3.2	42	+23
7	**5c**	Br	2.0	−40	6	15	1.9	49	—
8	**5c**	Br	2.0	−60	120	19	3.2	44	+26
9	**5d**	CF_3	1.2	−40	96	33	7.8	36	+59
10	**7a**	H	0.8	−40	36	71	8.1	51	+109
11	**7b**	Br	1.5	−40	36	69	8.2	67	+84
12	**7b**	Br	1.5	−40	36	84	5.4	59	+72
13	**7b**	Br	0.8	−60	96	24	4.1	63	+57

[a] Initiator, PF_5, 10 mol%; solvent, CH_2Cl_2.
[b] *p*-Substituent in benzoyloxy group.
[c] Methanol-insoluble polymer.
[d] By gel permeation chromatography, polystyrene standard.
[e] By ^{13}C NMR spectroscopy.
[f] In chloroform.
[g] The precision of this data is low because of the poor S/N ratio.

Table II. Polymerization of 1,6-anhydro deoxysugar derivatives having a 2-*O*-benzyl group

Entry No.	Monomer		Initiator		Solv.[a]	Temp	Time	Yield	M_n[b] $\times 10^{-4}$	β-Form[c]	Ref
	mmol		mol%		ml	°C	h	%		%	
1	**12a**	7.2	PF_5	5	2.5	−60	40 min	85	14	0	21
2	**12b**	5.0	SbF_5	5	1.0	−30	48	64	0.46	15	19
3	**12b**	5.0	SbF_5	5	1.0	−60	48	40	0.67	0	19
4	**13a**	2.9	PF_5	10	1.0	−60	40 min	95	7.8	0	21
5	**13b**	3.0	$SbCl_5$	3	1.0	−40	5	74	2.4	0	20
6	**13b**	3.0	SbF_5	3	1.0	−60	20	24	3.1	0	20

[a] CH_2Cl_2. [b] By gel permeation chromatography; polystyrene standard.
[c] By ^{13}C NMR spectroscopy.

5a—d, **7a**, and **7b** gave the polymers composed of both the corresponding α-form and β-form units. This is in sharp contrast to the finding that the 1,6-anhydro-β-D-galactose derivative **3** gave the stereoregular (1→6)-β-linked polysaccharide **4**.[12,13]

As the inserted expanded spectrum clearly shows, the signals due to the β-form unit appear as a pair of peaks (δ 102.7 and 102.3 ppm) with different intensities. The relative intensity of the lower field signal increased as the β-form content of the polymer increased. Therefore, the signal appearing at 102.7 ppm is presumably assignable to the anomeric carbon of the β–β consecutive diads, and the signal at 102.3 ppm to that of the β–α crossover diads. A similar splitting of the anomeric carbon signal was reported for the polymers of 6,8-dioxabicyclo[3.2.1]octane which is the skeleton of 1,6-anhydro sugars.[18]

Table II summarizes the previous results of the polymerization of the corresponding 1,6-anhydro sugar derivatives **12a**, **12b**, **13a**, and **13b** having a 2-*O*-benzyl group instead of a 2-*O*-benzoyl group.[19-21]

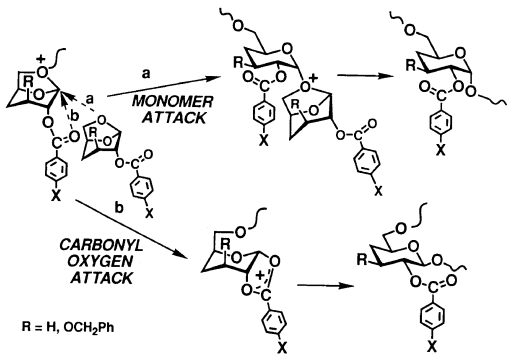
12a: D-monomer
12b: DL-monomer

13a: D-monomer
13b: DL-monomer

All these monomers gave the polymers solely composed of the respective α-form units except entry No. 2. Comparison of the data in Table I with those in Table II definitely indicates that the polymerization reactivities of the monomers **5b** and **7a** having a 2-*O*-benzoyl group are much lower than those of the corresponding monomers **12a** and **13a** having a 2-*O*-benzyl group.

One of the reasons for the significant decrease in the polymerization reactivities is that the carbonyl oxygen of the 2-*O*-benzoyl group competes with the acetal oxygen in the monomer in interacting with phosphorus pentafluoride, thus diminishing the fraction of the initiator available for initiation. Besides this effect, the greatly reduced polymerizabilities of the monomers **5a—d**, **7a**, and **7b** strongly suggest that these monomers propagate by a mechanism differing from the conventional one involving a trialkyloxonium ion.

As described in the introduction, the polymerization of the 1,6-anhydro galactose derivative **3** propagates through a mechanism involving the neighboring group participation of the 2-*O*-benzoyl group, giving (1→6)-β-D-galactopyranan **4** after deprotection.[12,13] It is highly probable that the polymerization of **5a—d**, **7a**, and **7b** also propagates by a similar mechanism. As illustrated in Scheme 2, a trialkyloxonium ion is attacked by the carbonyl oxygen of the 2-*O*-benzoyl group with inversion



Scheme 2. Propagation modes in the ring-opening polymerization of 1,6-anhydro deoxysugar derivatives having a 2-*O*-benzoyl group.

of the configuration of the anomeric carbon to form a dioxacarbenium ion. As a consequence, an incoming monomer can attack the reaction center entirely from the β-side of the pyranose ring to yield a (1→6)-β-linked structural unit, and the trialkyloxonium ion is regenerated. The propagation involving the neighboring group participation should be slow because of higher stability of the dioxacabenium ion compared with that of the trialkyloxonium ion.

All the polymers including those obtained in a relatively short reaction time (entry No. 7) were composed of both the respective (1→6)-α-linked and (1→6)-β-linked structural units. This implies that besides the propagation through the dioxacarbenium ion, direct monomer addition to the trialkyloxonium ion is very likely to take place competitively to give the corresponding (1→6)-α-linked structural unit.

The polymers obtained at a lower temperature had a higher β-unit content than the polymers obtained at a higher temperature (entry No. 3 *vs.* No. 2, and entry No. 5 *vs.* No. 8). This means that intramolecular nucleophilic substitution by the 2-*O*-benzoyl group to form the dioxacarbenium ion is more favorable at a lower temperature. An electron-withdrawing *p*-substituent on the 2-*O*-benzoyl aromatic ring increased the polymer yield but reduced the β-unit content of the polymers (entry No. 3 *vs.* No. 8, and entry No. 1 *vs.* No. 9). The carbonyl oxygen of the 2-*O*-benzoyl group bearing an electron-withdrawing group has a lower nucleophilicity and hence it is unfavorable for the neighboring group participation. This is another way of saying that the competitive propagation by the direct monomer addition to the trialkyloxonium ion becomes more preferable.

The polymer of the monodeoxygenated monomer **7b** having a 2-*O*-(*p*-bromobenzoyl) group had a higher β-content than the polymer of the corresponding dideoxygenated monomer **5c** under similar reaction conditions (entry No. 11 *vs.* No. 6). The difference can be explained by assuming that the direct monomer addition to the trialkyloxonium ion occurs less readily in the polymerization of **7b**, because of the higher steric hindrance between the growing chain end and the axial 3-*O*-benzyl group of the incoming monomer, when the monomer approaches the anomeric carbon of the trialkyloxonium ion from the α-side of the pyranose ring.

In this connection, the polymerization behavior of the 1,6-anhydro galactose derivative **3** is informative. It is much less reactive than the deoxygenated monomers examined here. Thus, a higher reaction temperature ($> -20°C$) was required to polymerize **3**, and the polymer yields were low. The markedly lower reactivity of **3** arises not only from the higher steric crowding when the monomer approaches the anomeric carbon of the trialkyloxonium ion of the growing chain end but also from the energetically unfavorable eclipsing between the bulky benzyloxy groups when the anhydro ring is opened and the pyranose ring is flipped. Conceivably, such a low reactivity of the monomer makes it possible for the polymerization to proceed entirely through the dioxacarbenium ion, thus giving the stereoregular (1→6)-β-linked polysaccharide **4**.

Another important factor that must be taken into account is transacetalization: Transacetalization involving polymer chains converts a

β-form unit into an α-form unit and *vise versa* as previously discussed in detail in the cationic polymerization of 6,8-dioxabicyclo[3.2.1]octane.[22] Transacetalization is more likely to take place for the polymers derived from the dideoxygenated monomers **5a**—**d**, because these polymers are composed of the less sterically crowded pyranose rings. Conformational energy estimation by using Angyal's parameters[23] indicates that both 3,4-dideoxy-α-D-*erythro*-hexopyranose and 4-deoxy-α-D-*xylo*-hexopyranose are slightly more stable than their β-counterparts. Therefore, in the polymerization of the monomers examined here, comparable proportions of the α-form and β-form units should coexist in the polymer chains obtained under the conditions where a thermodynamic equilibrium is attained.

Comparison of the data in Table I (entry No. 5 *vs.* No. 7) shows that the polymer obtained by a prolonged reaction had a lower content of the β-form unit than that obtained in a shorter time under the otherwise identical conditions. Therefore, it is very probable that transacetalization occurs in the polymerization of the dideoxygenated monomers **5a**—**d**, and perhaps to a less extent in the polymerization of **7a** and **7b**, even at −40°C or below. In fact, a dichloromethane solution of the (1→6)-α-linked polymer of **12a** was allowed to stand in the presence of phosphorus pentafluoride (10 mol%) at −40°C for 96 h to give a polymer composed of 59% (1→6)-α-linked units and 41% (1→6)-β-linked units. Therefore, it should be stressed here that ring-opening polymerization of 1,6-anhydro deoxysugar derivatives, particularly dideoxygenated monomers, should be carried out at temperature as low as possible and terminated in a short time, in order to minimize the configurational alteration of the anomeric carbons in the polymer chains by transacetalization.

The foregoing results and discussion led us to the following conclusion. In the polymerization of 1,6-anhydro-3,4-dideoxy-β-D-*erythro*-hexopyranose derivatives **5a**—**d** and 1,6-anhydro-4-deoxy-β-D-*xylo*-hexopyranose derivatives **7a** and **7b**, the neighboring group participation by the 2-*O*-(*p*-substituted benzoyl) group does occur to yield the corresponding (1→6)-β-linked units. However, the polymerization of these 1,6-anhydro deoxysugar derivatives could not fully be controlled so as to give the stereoregular (1→6)-β-linked polymers by the propagation involving the neighboring group participation. There are two probable reasons for the incomplete regulation of the polymer structure: One is the competitive propagation by the direct monomer addition to the trialkyloxonium growing chain end, and the other is the transacetalization of the polymer chains.

In the polymerization of **3** giving the entirely (1→6)-β-linked polymer **4**,[12,13] it would appear that the direct monomer addition to the trialkyloxonium growing chain end is highly unfavorable in comparison with the intramolecular nucleophilic reaction of the carbonyl oxygen of the 2-*O*-benzoyl group. In addition, transacetalization of the polymer chains is much less likely to take place, because of the enhanced steric hindrance between the growing chain end and the additional axial 4-*O*-benzyl group in the polymer chain, when the growing chain end adds to an exocyclic acetal oxygen in the polymer chain to form a linear trialkyloxonium ion.[22]

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