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Synthesis of thiosaccharides employing the Pummerer rearrangement of tetrahydrothiopyran oxides☆

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Abstract—The Pummerer rearrangement of 1-deoxy-5-thioglucopyranose derivatives carrying acetonides at the C3,4-positions proceeded regioselectively at the C1 position by treating with TFAA in the presence of pyridine. Studies employing deuterium-labelled derivatives revealed that the reaction was induced by E2 1,2-elimination of trifluoroacetic acid of the trifluoroacetoxy sulfonium intermediate. This methodology was applied to the synthesis of an isomaltotriose derivative consisting of 5-thioglucopyranoside units.

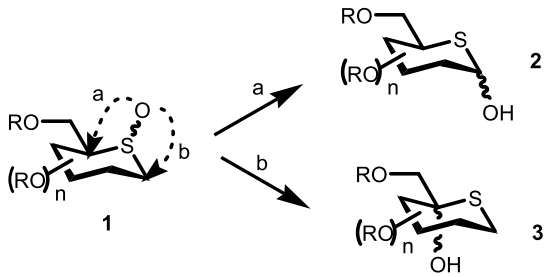
1. Introduction

Carbomimetics, analogues which structurally mimic carbohydrates, are candidates not only as potent probes in the mechanistic investigation of glycosidases but also as novel drugs for some digestive or infective diseases.[1–7] We have made efforts towards the synthesis of oligosaccharide derivatives consisting of 5-thiopyranoses based on the concept that replacement of the oxygens in the pyranose rings of oligosaccharides with sulfur atoms may realize tolerance against glycosidases with minimum structural alterations.[8,9] As part of these studies, we have discovered that the Pummerer rearrangement of thiopyranose oxides having O-3 and O-4 protected as an O-isopropylidene derivative proceeded and reported this finding as a communication.[10] Further investigation employing deuterium-labelled derivatives enabled us to discuss details of the reaction. Now, we would like to report the details of these studies and an application of this strategy to a synthesis of sulfur-substituted isomaltotrioside.

2. Results and discussions

2.1. Basic methodology

Since the Pummerer rearrangement provides a synthetic equivalent of carbonyl compounds from sulfoxides, an equivalent for alcohols, under non-oxidative conditions, it has been utilized in total syntheses of natural products as an alternative protocol for oxidation of the alcohols.[11,12] This rearrangement will be desirable for introduction of the C1 hemithioacetal function of thiosugars if we can perform the rearrangement of 1-deoxy-5-thiopyranose oxides at the C1 position regioselectively as shown in Scheme 1.[13] In spite of extensive studies by Oae[14,15] and Crucianelli[16] on the Pummerer rearrangements, the regioselectivity for highly functionalized asymmetric sulfoxides has not been fully discussed. Recently, Naka et al.[17,18] and Zhang et al.[19] independently investigated regio- and stereoselective formation of thionucleosides via Pummerer-type



Scheme 1. Basic strategy.

☆ Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2004.06.006

Keywords: Thiosaccharids; Pummerer rearrangements; Reaction mechanism; Isomaltotriose analogue.

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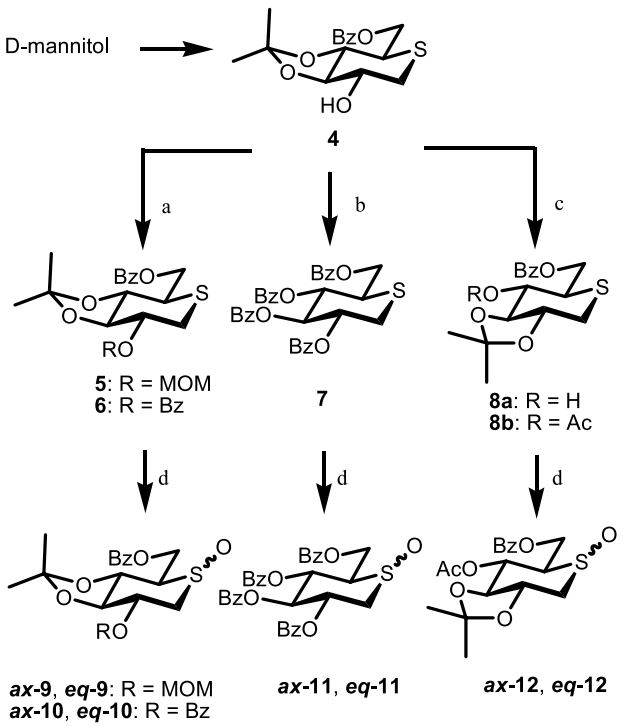
glycosidation. However, the factors determining regioselectivity have not been fully elucidated. Thus, we had to study the reaction courses caused by the differences in the stereochemistry of the sulfoxides and in the protective groups at the C2–C6 positions in the rearrangement.

2.2. Preparation of 1-deoxy-5-thio-D-glucopyranose oxides

We first synthesized axial and equatorial oxides of 1-deoxy-5-thioglucopyranoses carrying a series of protective groups **9**-**12** (Scheme 2). Thiane **4** was readily prepared from D-mannitol following the protocol reported by Merrer et al.[20] The hydroxy group of **4** was protected in the form of methoxymethyl (MOM) ether under usual conditions to give **5** in 86% yield. The sulfide function of **5** was oxidized to the sulfoxide with *m*-chloroperbenzoic acid (*m*CPBA) in CH_2Cl_2 at −20 °C for 30 min. This oxidation proceeded without stereoselectivity, giving a separable mixture (50:50) of the axial- and equatorial-sulfoxides, *ax*-**9** and *eq*-**9**, in 87% yield. In a similar manner, **4** was converted into the benzoates *ax*-**10** and *eq*-**10** in good overall yield. Benzoylation after removal of the acetonide of **4** gave **7** in 85% yield in two steps. The acetonide group of **4** migrated to the C2–C3 positions (carbohydrate numbering) by treatment of **4** with *p*-toluenesulfonic acid in acetone to afford **8a** (60%) along with recovery of **4** (32%). The hydroxy function of **8a** was protected as the acetate, giving **8b** in quantitative yield. In a similar manner described for **9** and **10**, sulfides **7** and **8b** were converted into both isomeric mixtures of sulfoxides **11** and **12**, respectively. Those isomers could also be readily separated by silica gel column chromatography.



Scheme 2. Reagents and conditions: (a) for **5**; MOMCl, $^{i}Pr_2NEt$, CH_2Cl_2, 0 °C (86%), for **6**; BzCl, pyridine, rt (95%); (b) (i) cat. HCl, MeOH, rt (85%), (ii) BzCl, pyridine, rt (100%); (c) (i) cat. *p*-TsOH, rt, acetone, then separation, (ii) Ac_2O, pyridine, rt (100%); (d) *m*CPBA, CH_2Cl_2, −20 °C (**9**, 87%, **10**, 91%, **11**, 96%, **12**, 92%, isomeric ratios (*eq*/*ax*) **9**: (50:50), **10**: (60:40), **11**: (50:50), **12**: (60:40).

2.3. Stereochemistry of the sulfoxides

Stereochemistries of the sulfoxide moieties of **9**-**12** were next studied. Since there were few precedents regarding the effect of stereochemistry of sulfoxides on the regioselectivity in the Pummerer rearrangements, assignment of those stereochemistries was required. In the ^1H NMR spectra of both isomers of **9**-**12**, large coupling constants for $J_{C1Hax,C2H}$, $J_{C2H,C3H}$, $J_{C3H,C4H}$, and $J_{C4H,C5H}$ (carbohydrate numbering) of the tetrahydrothiopyran ring moieties

Table 1. The characteristic ^1H- and ^{13}C NMR chemical shifts of sulfoxides **9**-**12** and their differences $\Delta\delta$ (=$\delta(eq)-\delta(ax)$, italic) and the coupling constants for $J_{C1Heq-C1Hax}$ and $J_{C5H-C6H}$

Signals	**9**[a]			**10**[a]			**11**[b]			**12**[a]		
	eq	*ax*	Δδ	*eq*	*ax*	Δδ	*eq*	*ax*	Δδ	*eq*	*ax*	Δδ
C1H*ax*	2.75	1.69	*+1.06*	2.66	1.58	*+1.08*	3.22	2.72	*+0.50*	2.55	1.63	*+0.92*
C1H*eq*	3.32	3.20	*+0.12*	3.24	3.33	*−0.09*	4.02	3.85	*+0.17*	3.28	3.03	*+0.25*
C2H	3.63	4.62	*−0.99*	5.32	6.13	*−0.81*	5.45	6.10	*−0.65*	3.05	4.61	*−1.56*
C5H	2.69	2.53	*+0.16*	2.82	2.65	*+0.17*	3.49	3.38	*+0.11*	2.73	2.52	*+0.21*
C1	55.4	50.6	*+4.8*	53.4	49.2	*+4.2*	52.6	47.4	*+5.2*	52.2	48.1	*+4.1*
C2	69.2	71.1	*−1.9*	67.8	69.3	*−1.5*	65.3	67.3	*−2.0*	69.1	71.6	*−2.5*
C4	71.0	72.7	*−1.7*	71.4	72.9	*−1.5*	64.8	67.9	*−3.1*	65.0	68.9	*−3.9*
C5	64.2	58.8	*+5.4*	64.8	59.2	*+5.6*	65.7	59.0	*+6.7*	67.0	60.6	*+6.4*
$J_{C1Heq-C1Hax}$	*12.2*	*14.6*		*12.7*	*14.1*		*11.8*	*14.2*		*10.7*	*13.2*	
$J_{C5H-C6H}$	*3.0* *4.4*	*4.4* *11.7*		*3.4* *5.4*	*4.4* *11.2*		*2.5* *2.5*	*4.9* *9.3*		*3.0* *4.8*	*3.9* *9.8*	

[a] Observed in C_6D_6.
[b] Observed in $CDCl_3$.

suggested that those protons are in axial orientations. Thus, the tetrahydrothiopyran rings of isomers **9-12** adopt $^4C_1$ conformations. The characteristic signals in their ^{1}H- and ^{13}C NMR spectra are shown in Table 1. Signs of the $\Delta\delta$ value [$=\delta$(*eq*-isomer)$-\delta$(*ax*-isomer)] are consistent with the literature[21] without exception about the C2H, C4H, and C5H signals in the ^{1}H NMR spectra as well as resonances due to C1, C2, C4, and C5 in the ^{13}C NMR spectra. The coupling constants, $J_{C1Heq-C1Hax}$ (geminal coupling), for axial sulfoxides *ax*-**9-12** were larger than those of the corresponding equatorial isomers *eq*-**9-12**, which also supported those stereochemistries according to Eliel's report.[22–24]

The stereochemistries of these sulfoxides were studied further. In the axial sulfoxide (*ax*-isomer), the electron-donating oxide moiety should shield the *anti*-periplanar-orientated axial proton (C1H*ax*) of the C1 position as shown in Figure 1[22,25,26] In contrast, the lone pair electrons of the equatorial sulfoxide (*eq*-isomer) did not induce the above effect for the C1H*ax*. This suggested that the signs of the $\Delta\delta$ values for C1H*ax* should be positive. On the other hand, the $\Delta\delta$ values for the C1H*eq* are expected to be small, since the sulfoxide moiety equally affected those protons because of the *gauche* relationships between the oxygen of the sulfoxides and the C1 equatorial protons for both axial and equatorial sulfoxides. The observed $\Delta\delta$ values for the C1H*eq* accorded with the discussion. These $\Delta\delta$ values were also supported by theoretical calculations for tetrahydrothiopyran oxides employed as the model molecules. The estimated chemical shifts for the C1 methylene protons (carbohydrate numbering) of the axial thiane oxide *ax*-**14** and the corresponding equatorial isomer *eq*-**14** are shown in Figure 2. These chemical shifts were calculated using Spartan 04.[27] Optimization of these structures was performed prior to the calculations of their chemical shifts. In order to take the contribution of the *d*-orbitals of the sulfur atoms into account, the 6-31G* basis set[28] was employed for these computations. The chemical shifts of the C1H*ax* (carbohydrate numbering) in the axial isomer *ax*-**14** was predicted to appear at higher field than those of the corresponding equatorial isomer *eq*-**14** and sulfide **13**.

2.4. The Pummerer rearrangement of sulfoxides 9-12

With the sulfoxides **9-12** in hand, Pummerer rearrangements were attempted. The rearrangement did not proceed at room temperature when acetic anhydride (Ac_2O) was employed.[29] The heating conditions with Ac_2O resulted in the formation of complex mixtures in the cases that both *ax*- and *eq*-**11** were employed. Preparative TLC after refluxing *ax*-**9** and Ac_2O in pyridine gave only trace amounts of **15** and thiane **5**.

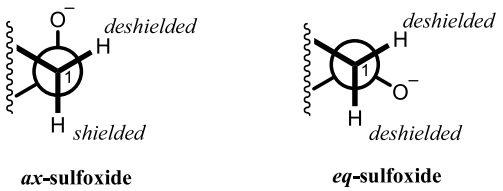


Figure 1. Shielding and deshielding of the C1 protons by the sulfoxide oxygen.

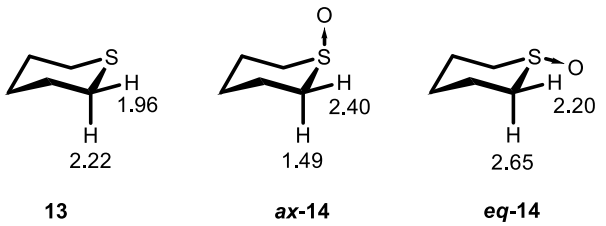
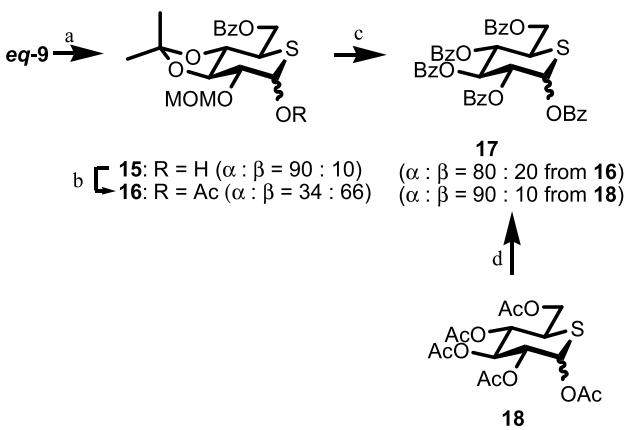


Figure 2. Estimated chemical shifts (ppm) of the α-methylene protons of thiane and its oxides.[25]

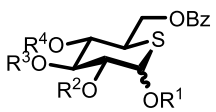
The conditions using trifluoroacetic anhydride (TFAA) in place of Ac_2O, the modified protocol developed by one of present authors,[12] was found to promote the rearrangement smoothly at room temperature. Thus, the treatment of *eq*-**9** with TFAA (5.0 equiv.) in the presence of pyridine (10 equiv.) in CH_2Cl_2 at room temperature for 3 h realized the rearrangement in highly stereoselective manner, providing 5-thioglucopyranose derivative **15** as shown in Scheme 3. The trifluoroacetyl group introduced was hydrolyzed during the work-up. The existence of the OH group in **15** was confirmed by observing strong absorption at 3440 cm^{-1} (broad) in the IR spectrum. The ^{1}H NMR spectrum indicated that **15** exists as a 90:10 anomeric mixture. Since **15** appeared as a broad spot on the TLC due to the equilibrium between the anomers, the accurate yield of **15** after silica gel column chromatography in this reaction could not be obtained. It was estimated to be 66% after acetylation, giving an anomeric mixture (α/β=34:66) of **16**. Those isomers could be separated by preparative silica gel TLC. The structure of **16** was confirmed after converting it into pentabenzoate **17**. Treatment of the α-isomer of **16** with aqueous trifluoroacetic acid promoted hydrolysis of the acetonide and the C1 acetyl group. The following benzoylation under usual conditions gave **17** as an inseparable mixture (α/β=80:20) in 63% yield in two steps. The ^{1}H NMR spectrum of this sample was identical, except for the isomeric ratio, with that of **17** prepared from 5-thioglucopyranosyl peracetate **18**[30] by saponification and the subsequent benzoylation. The isomeric ratio of **17** prepared from **18** was α/β=90:10.

The rearrangements for other congeners *eq*-**10-12** were also

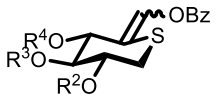


Scheme 3. The Pummerer rearrangement of *eq*-**9**. Reagents and conditions: (a) TFAA, Py, CH_2Cl_2, rt; (b) Ac_2O, Py, rt, then separation (66% two steps); (c) (i) *aq*. TFA, rt, (ii) BzCl, Py, rt (63% two steps); (d) (i) NaOMe, MeOH, rt, (ii) BzCl, Py, rt (67% two steps).

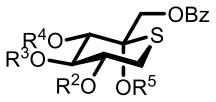
Table 2. Products obtained by Pummerer rearrangement of sulfoxides **9**-**12**



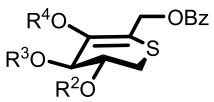
20: R^1 = H, R^2 = Bz, R^3, R^4 = acetonide
24: R^1 = H, R^2, R^3, R^4 = Bz
29: R^1 = H, R^2, R^3 = acetonide, R^4 = Ac



19: R^2 = MOM, R^3,R^4 = acetonide
21: R^2 = Bz, R^3,R^4 = acetonide
25: R^2, R^3,R^4 = Bz
30: R^2, R^3 = acetonide, R^4 = Ac



22: R^2 = Bz, R^3, R^4 = acetonide, R^5 = H
23: R^2 = Bz, R^3, R^4 = acetonide, R^5 = TFA
26: R^2, R^3, R^4 = Bz, R^5 = H
27: R^2, R^3, R^4 = Bz, R^5 = TFA
31: R^2, R^3 = acetonide, R^4 = Ac, R^5 = H
32: R^2, R^3 = acetonide, R^4 = Ac, R^5 = TFA



28: R^2, R^3, R^4 = Bz

Run	Sulfoxides	5-Thioglucose derivatives (α/β, yields)	Other products
1	*eq*-**9**	**15** (34:66, 66%)[a]	Not detected
2	*ax*-**9**	**15** (34:66, 84%)[a]	**19**[b] (trace)
3	*eq*-**10**	**20** (91:9, 55%)	**21**, **22**, **23** (trace each)[b]
4	*ax*-**10**	**20** (90:10, 61%)	**21**, **22**, **23** (trace each)[b]
5	*eq*-**10**	**20** (90:10, 66%)[c]	Not detected
6	*ax*-**10**	**20** (90:10, 65%)[c]	Not detected
7	*eq*-**11**	**24** (90:10, 5.7%)	**25** (4.0%), **26** (50%), **27** (8.9%)[d], **28** (9.5%)
8	*ax*-**11**	**24** (90:10, 2.7%)	**25** (0.3%), **26** (41%), **27** (5.6%)[d], **28** (8.9%)
9	*eq*-**12**	**29** (not detected)	**30** (14%), **31** (40%), **32** (1.7%)[d]
10	*ax*-**12**	**29** (not detected)	**30** (9.4%), **31** (45%), **32** (1.2%)[d]

[a] The isomeric ratio and yield were determined after acetylation (→**16**).
[b] Structures of minor **19**, **21**, **22**, and **23** were assigned by comparing those ^{1}H NMR spectra with those of the corresponding compounds **25**-**32**.
[c] Pyridine was employed as the solvent.
[d] Structures of **27** and **32** were estimated based on the product obtained by treating with Et_3N in methanol.

investigated. The results are summarized in Table 2. In the reaction of *eq*-**10**, carrying benzoate in place of the MOM group of **9**, the rearrangement occurred in similar selectivity to that of **9**, giving 5-thioglucopyranose derivative **20** in 55% yield along with trace amounts of other products **21**-**23** (run 3). Products **21**-**23** were obtained via the rearrangement to the C5 position. The structures of **21**-**23** could not be fully determined because of their trace amounts; however, those were tentatively assigned by comparing their ^{1}H NMR spectra with those of **25**-**32** (vide infra). An attempt employing pyridine as the solvent slightly improved the yield of desired **20** (run 5).

In contrast, the rearrangement for perbenzoate *eq*-**11** proceeded at the C5 position predominantly to give undesired 5-hydroxy derivative **26** (50%), the corresponding trifluoroacetate **27** (8.9%), *exo*-olefin **25** (4.0%), and *endo*-olefin **28** (9.5%) (run 7). 5-Thioglucose derivative **24** was obtained as a minor product (5.7%) by this experiment. Interestingly, anomers α-**24** and β-**24** could be separated by silica gel column chromatography, whereas the corresponding anomers of **15** were inseparable due to equilibration. Trifluoroacetate **27** was not stable enough to obtain its spectral data; however, two-dimensional silica gel TLC analysis of **27** disclosed that **27** was easily transformed into the corresponding alcohol **26**. This observation suggested that **27** was a trifluoroacetate ester of **26**. Alcohol **26** was produced as a single isomer at C5; the stereochemistry of **26** and **27**, however, could not be assigned by NOE studies. The stereochemistry of **26** was tentatively assigned as 5*R* (carbohydrate numbering) taking the anomeric effect into account. *exo*-Olefin **25** was obtained as a single isomer, but assignment of the stereochemistry for the C5–C6 double bond has remained unclear.

Notably, when 2,3-*O*-acetonide *eq*-**12** was subjected to the Pummerer reaction, the rearrangement proceeded with higher regioselectivity at the C5 position (carbohydrate numbering) to give a mixture of **30**-**32** (run 9). Thioglucopyranose **29**, obtainable through the rearrangement at the C1 position, was not observed under these conditions.

Axial sulfoxides *ax*-**9**-**12** were also subjected to the Pummerer reaction under similar conditions (run 2, 4, 6, 8, and 10). The same products as those provided from the corresponding equatorial sulfoxides were afforded in similar yields. Noteworthily, *ax*-**9** gave **16** in 84% yield after acetylation. It seems that the stereochemistry of the sulfoxide moiety is not important for the regioselectivity in the rearrangement based on these observations. This is inconsistent with Naka's report,[17] disclosing the stereochemistry of sulfoxides contributes significantly to the regioselectivity, although TMSOTf was used as the activator.

The regioselectivities are next discussed. Acetonides **9** and **10** carry an electron-withdrawing benzoate ester and an electron-donating MOM ether, respectively, at their C2

positions (carbohydrate numbering). These protective groups were expected to affect the stability of the cationic intermediates produced during the Pummerer rearrangement. However, **9** and **10** provided similar results. Accordingly, an electrostatic factor might contribute less to the regioselectivity. On the other hand, the position of the acetonide group dramatically influenced the selectivity as mentioned above. Thus, the relationship between the selectivity and the conformation of the ring moieties of **9**-**12** was investigated using molecular modeling calculations.[31] Model compounds **X**, **Y**, and **Z** were selected in order to save the time required for the calculations. Since these model compounds involve sulfoxide functions, an ab initio method based on the 6-31G* basis set was employed. The results are summarized in Table 3.

In the cases of bicyclic **Y** and **Z**, the annular bond angles of the carbons, where the rearrangement occurs mainly in the experiments (∠S–C5–C4 for **Y**, ∠S–C1–C2 for **Z**), were suggested to be around 115°. This angle approximates that of sp^2 carbons. Thus, these carbons can be easily transformed to the planar sp^2 thiocarbenium intermediate. On the other hand, the angles for the other sites (∠S–C1–C2 for **Y**, ∠S–C5–C4 for **Z**) were estimated to be around 105°, which is rather small comparing to that of the standard sp^3 carbon. So, these carbons might remain intact during the reactions. While there was no remarkable difference between the angles ∠S–C1–C2 and ∠S–C5–C4 for monocyclic **X** according to similar calculations, the Pummerer rearrangement of **11** proceeded selectively at C5. This can be explained by considering the Saytzeff rule.

The rearrangement must provide the C1–OTFA esters as the intermediate. However, the TFA ester moieties of them were converted into C1–alcohols during the work up. This might proceed by hydrolysis of the ester moiety (retention) and/or substitution with hydroxyl group at C1 position (inversion). Further, many of the C1–OH derivatives of 5-thiosugars are under equilibrium between anomers. Thus, the stereochemistry of the addition of the trifluoroacetate ion remains unclear. The *O*-benzoyl group at C2 position of thiosugars may not induce β-stereoselectivity, so called the neighboring effect, in this steps based on our experiences,[9] although *O*-acyl function at C2 contributes for the β-addition in regular carbohydrate chemistry.

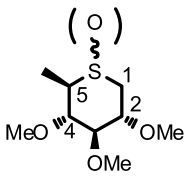
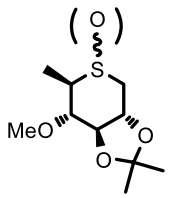
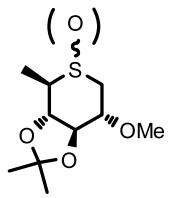
2.5. Mechanistic studies on the Pummerer reaction

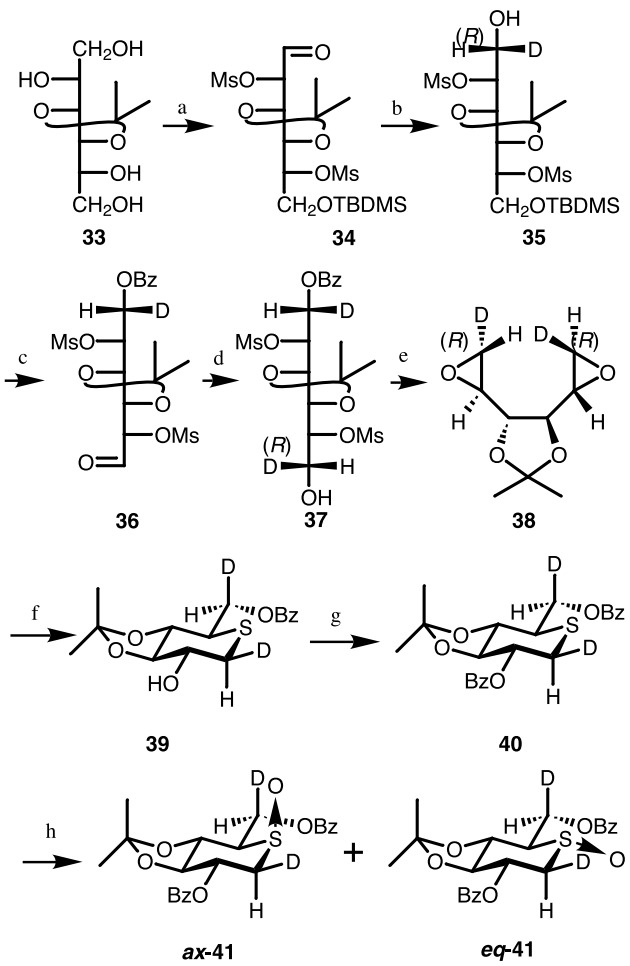
2.5.1. Preparation of deuterium-labelled sulfoxides *ax*-41 and *eq*-41. Exposing the sulfoxide *eq*-**10** to the Pummerer conditions (TFAA, Py-CH_2Cl_2), at a lower temperature (0 °C) for a shorter period (20 min) afforded the *ax*-**10** in 60% yield along with the rearranged product **20** (27%). This observation suggests the occurrence of epimerization of the sulfoxide moiety under the conditions we employed. Oae et al. reported mechanistic details about the Pummerer rearrangement of thianes;[14] however, epimerization of the sulfoxide moiety during the Pummerer reaction was not mentioned. Thus, there might be some difference in the reaction pathways from that which they reported. In order to examine the reaction details, the Pummerer rearrangement employing both isomers of deuterium-labelled derivatives *ax*- and *eq*-**41** was next attempted.

Preparation of isomeric pair of **41** were achieved by modifying Merrer's protocol.[20] Deuterium atoms were required to be introduced stereoselectively at the C1 position of 1-deoxy-5-thioglucopyranose derivatives for our purpose (Scheme 4). We designed stereoselective reduction of the aldehyde **34** for the introduction of the deuterium atom. The aldehyde **34** was prepared from **33** by a sequence of the reactions: (i) protection of both terminal alcohols of 3,4-*O*-isopropylidene mannitol in forms of the *tert*-butyldimethylsilyl (TBDMS) ethers, (ii) mesylation (iii) partial deprotection of the silyl ether by treatment with 1 equiv. of tetrabutylammonium fluoride (TBAF) in the presence of acetic acid, and (iv) oxidation with Dess-Martin reagent.[32]

It was found that reduction of **34** with sodium borodeuteride in the presence of cerium (III) chloride in methanol[33] took place stereoselectively, giving alcohol **35** in 91% yield with (1*R*)-configuration. The stereoselectivity was estimated to be 90:10 judging from its ^1H NMR spectrum. The stereochemistry of the newly introduced deuterium was established at a later stage of the synthesis. The reduction

Table 3. Bond angles ∠S–C1–C2 and ∠S–C5–C4 of the model sulfoxides suggested by molecular modeling calculations (6-31G*)

Model	 **X**	 **Y**	 **Z**
∠S–C1–C2			
Sulfide	112.2	107.3	115.3
eq-Oxide	112.1	106.5	116.3
ax-Oxide	112.6	107.7	116.2
∠S–C5–C4			
Sulfide	110.9	113.9	106.3
eq-Oxide	110.6	114.6	105.4
ax-Oxide	111.1	114.3	106.5



Scheme 4. Reagents and conditions: (a) (i) TBDMSCl, Et_3N, DMF, rt (100%), (ii) MsCl, Et_3N, CH_2Cl_2, 0 °C (99%), (iii) TBAF, AcOH, THF, 0 °C (67%), (iv) Dess-Martin reagent, CH_2Cl_2, rt (100%); (b) $NaBD_4$, $CeCl_3$, MeOH, rt (91%); (c) (i) BzCl, Py, CH_2Cl_2, rt (90%), (ii) TBAF, AcOH, THF, rt (98%), (iii) Dess-Martin reagent, CH_2Cl_2, rt; (d) $NaBD_4$, $CeCl_3$, MeOH, rt (85% two steps); (e) K_2CO_3, MeOH, CH_2Cl_2, 0 °C (67%); (f) (i) Na_2S, DMF, rt (77%), (ii) DEAD, PPh_3, benzoic acid, THF, rt (94%); (g) BzCl, Py, CH_2Cl_2, rt (72%); (h) *m*CPBA, CH_2Cl_2, 0 °C (74%, *ax*-**41**/*eq*-**41**=60:40).

with sodium borodeuteride or zinc borodueteride[34,35] in various solvents was found to be ineffective for the stereoselectivity. Since our synthetic route adopted *C*2 symmetrical **38** as a key intermediate, deuterium atom had to be introduced also at another terminal carbon with the same configuration in order to obtain the labelled substrate with the deuterium atom at the C1 position (carbohydrate numbering) in high concentration. Thus, after the TBDMS group of **35** was removed, the regenerated alcohol moiety was oxidized again under the same conditions as above to give aldehyde **36**. As expected, the reduction with cerium (III) chloride–sodium borodeuteride in methanol introduced deuterium in the same stereoselectivity (90:10), giving alcohol **37** in high yield. Then, **37** was converted into Merrer's bisepoxide **38** in 67% yield by treatment with potassium carbonate in methanol at 0 °C. Bisepoxide **38** thus prepared was converted into 1-deoxy-5-thioglucose derivative **39** according to their report. Treatment of **38** with sodium sulfide in methanol gave the corresponding thiepane, which was followed by ring contraction reaction under the Mitsunobu conditions[36] to provide **39** in 72% yield in two steps. In the same manner as that for **4**, the alcohol function of **39** was converted into benzoate giving **40** in 72% yield. Oxidation of the sulfide group proceeded smoothly to provide *ax*-**41** and *eq*-**41** in good yields.

The stereochemistries of deuterium-labelled carbons of **41** were next determined. The ^{1}H NMR spectrum of **40** was quite similar to that of **6** except for the disappearance of two signals for the C1H (δ 2.78 ppm) and one of the C6 methylene protons (δ 4.27 ppm) owing to incorporation of the deuterium atoms[37] as shown in Figure 3. The coupling constant between the remained C1H (2.35 ppm) and C2H was 9.8 Hz, which suggests that the equatorial proton was substituted with deuterium. Accordingly, the configuration at the C1 position was estimated to be (*S*).

The signal for the remained C6H appeared as a doublet (J=3.9 Hz) at 4.82 ppm. Comparing the coupling constant with that between C5H and C6H in **6** (7.8 Hz) and taking also the *gauche* effect[38] into account, the stereochemistry at the C5 position should be (*R*). This indicates that the stereochemistries of the primary alcohol moieties of **35** and **37** were both (*R*)-configuration. Thus, the reduction of both **34** and **36** was presumed to have proceeded through the six-membered chelation intermediate.[39]

The ^{1}H NMR spectra of the labelled sulfoxides *ax*-**41** and *eq*-**41** displayed good accordance with those of the non-labelled *ax*-**10** and *eq*-**10**, respectively. These comparisons of the ^{1}H NMR spectra as well as the R_f values on silica gel TLC made their stereochemistry incontestable as depicted in Scheme 4.

2.5.2. Discussion about the mechanism of the Pummerer rearrangement based on the results employing *ax*-41 and *eq*-41. The Pummerer rearrangements were examined employing the labelled substrates *ax*-**41** and *eq*-**41** thus in hand. As expected, the rearrangement of both *ax*-**41** and *eq*-**41** took place smoothly by treating with TFAA in the

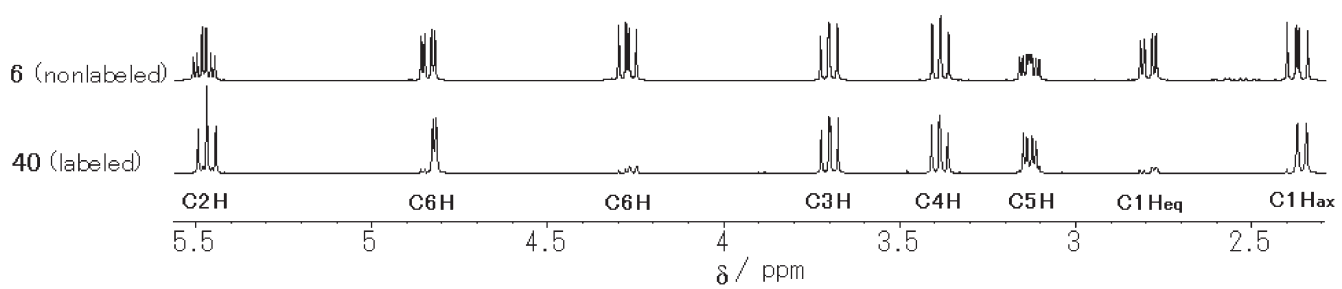
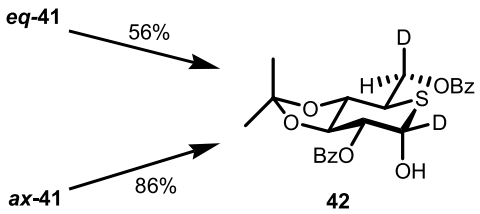


Figure 3. Part of ^{1}H NMR spectra (2.3–5.6 ppm) of **6** (non-labelled, upper) and **40** (labelled, lower) in C_6D_6.

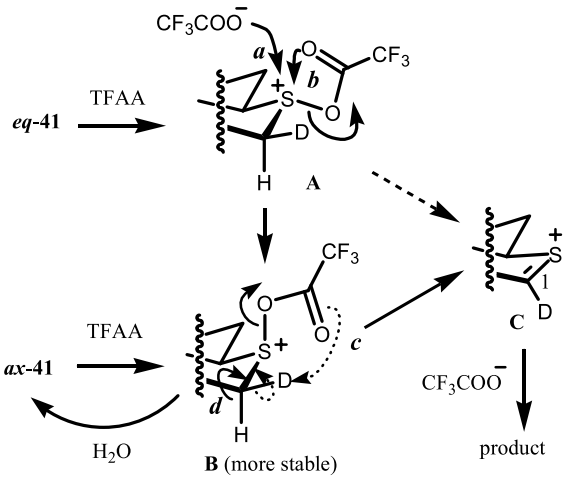
presence of pyridine in CH_2Cl_2 at room temperature, giving **42** in 56 and 86%, respectively (Scheme 5). The structure of **42** was confirmed by comparing the ^{1}H NMR spectrum to that of **20**. The ^{1}H NMR spectrum suggested that the deuterium atom was completely retained through the reaction. Interestingly, the ^{1}H NMR spectrum suggested that **42** existed as a single isomer, while **20** was observed as a anomeric mixtures (α/β=91:9). Since anomers **20** were under equilibrium on the basis of two-dimensional silica gel TLC, this might be caused due to isotope effect after conversion of the corresponding trifluoroacetate into **20**. The signal corresponding to C1H was not detected in the ^{1}H NMR spectrum of **42**. Due to the absence of the C1H signal, the stereochemistry of the anomeric position could not be established from the coupling constant. However, the stereochemistry for the C1 position could be assigned to be (*S*)-configuration by taking into account the spectral profile of other signals in the ^{1}H NMR spectrum as well as its behavior on silica gel TLC.

Since there was only small difference in the yields between the reaction of the labelled and non-labelled substrates, it is unlikely that the deuterium atom at the C1 position affected the reaction process.



Scheme 5. The Pummerer rearrangement of deuterium labelled *eq*-**41** and *ax*-**41** by TFAA.

As mentioned in Section 2.5.1, we observed a complete epimerization at the sulfoxide moieties of non-labelled *eq*-**10** into *ax*-**10** by quenching at the early stage of the Pummerer reaction. Similar isomerization took place under the same conditions also in the case of labelled *eq*-**41**. Thus, this isomerization might occur generally under these conditions. The isomerization of sulfonium ion **A** to **B** may proceed through intermolecular path a or intramolecular path b as shown in Scheme 6, although we cannot figure out at this stage which pathway predominantly contributes to the isomerization process. Probably, thiocarbenium ion **C** might be formed from sulfonium **B**, because not even trace amounts of the axial sulfoxides were detected on the silica gel TLC in the reactions of the equatorial sulfoxides. The sulfonium ion **B** seemed to be hydrolyzed to sulfoxides on the silica gel TLC and also during the work-up, giving the axial sulfoxides. Inversion of **A** by a hydroxy anion can be ruled out because of the existence of excess TFAA that consumes H_2O quickly. In the process **B** to **C**, the possibility of intramolecular pericyclic deprotonation (path c)[40,41] can be eliminated, because only the C1H*ax* was lost exclusively (path d) during the reaction in our experiments. Indeed, the ^{1}H NMR spectrum of **42** did not display the anomeric proton. These are consistent with Oae's report disclosing that the Pummerer rearrangement of cyclic sulfoxides proceeds through E2 1,2-elimination.[14] As mentioned above, the stereochemistry of the addition step of the trifluoroacetate



Scheme 6.

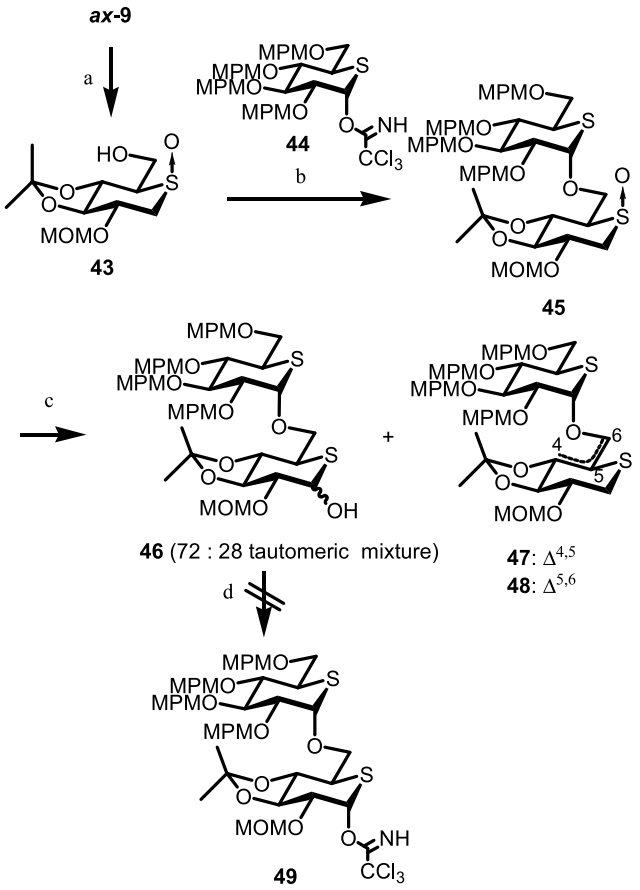
ion was unclear because of epimerization during and/or after work up, giving **42**.

However, as regards the reaction mechanism for the equatorial isomer, our results were different from that reported by Oae et al. In our experiments, the deuterium atom at the C1 position was also retained after the Pummerer reaction of *eq*-**41**, which indicates that the bond between C1 and the axial proton bond was cleaved under the conditions. In contrast, Oae disclosed that the C2 equatorial proton of octahydro-2*H*-thiocromene was removed by E2 1,2-elimination after flipping the thiane ring to the twisted boat conformation in the case of equatorial sulfoxide. It is hard to explain the detail of this difference at this stage, because a complex mixture was obtained when we attempted the rearrangement of *eq*-**41** under their conditions (heating with dicyclohexylcarbodiimide, Ac_2O). In our case, the potent leaving ability of the trifluoroacetoxy group might accelerate the elimination step giving thiocarbenium ion **C** at lower temperature and this might give rise to the difference in the reaction mechanisms (Scheme 6).

2.6. Synthesis of sulfur substituted isomaltotriose 58 as an application

Since the sulfur atom, a member of carcogen, is expected to exhibit similar chemical and physical properties to the oxygen atom, sulfur-substituted analogues of oligosaccharides may be useful inhibitors against the glycosidases.[8,42] We applied this rearrangement to a synthesis of sulfur-substituted isomaltotriose **58** in order to examine its scope and limitation.

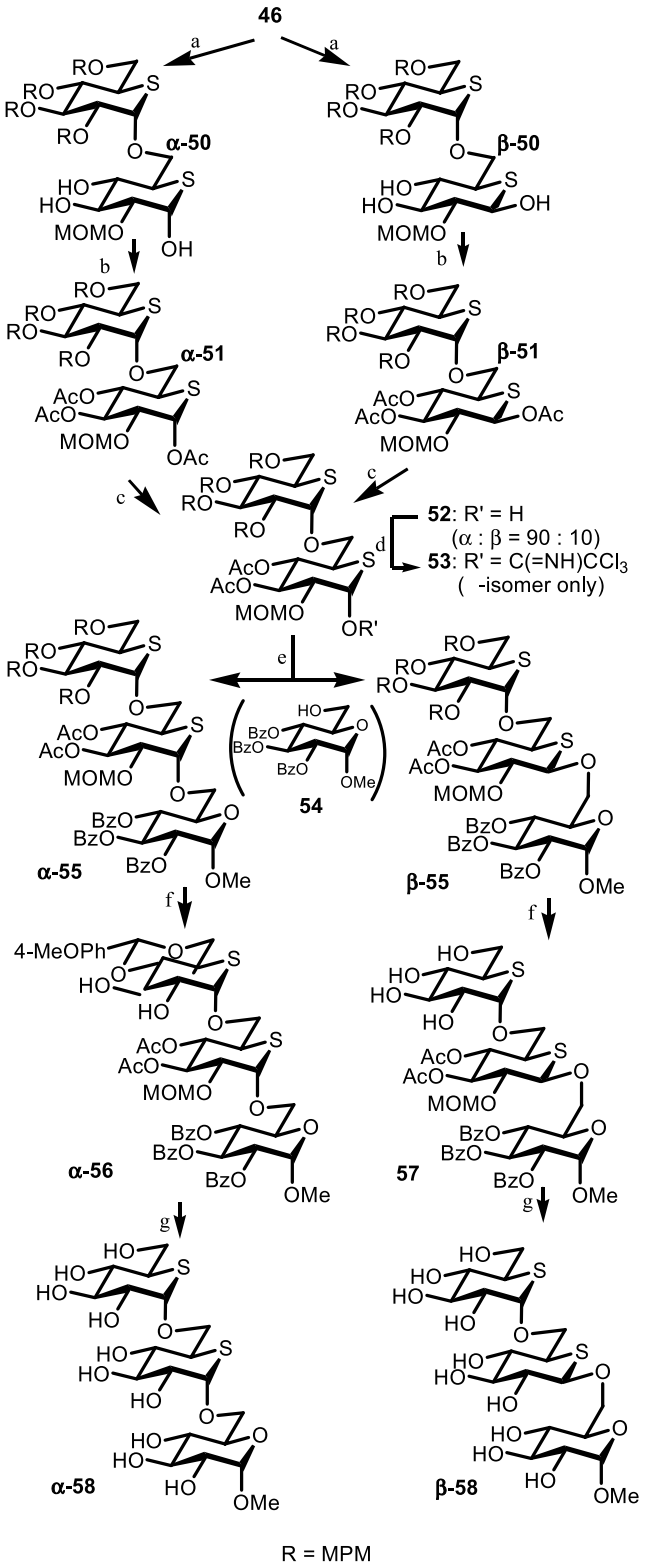
The benzoyl group of *ax*-**9** was removed by sodium methoxide in methanol. The resulting alcohol **43** was coupled with thioglucopyranosyl trichloroacetimidate **44**[8] in the presence of a catalytic amount of trimethylsilyl trifluoromethanesulfonate (TMSOTf)[43] in CH_2Cl_2, giving the α-glycoside **45** stereoselectively[8] in 93% yield (Scheme 7). Production of the isomer of **45** with β-glycoside linkage was not detected in this reaction. Stereochemistry of the newly introduced α-glycoside of **45** was confirmed by observing a small coupling constant between C1′H and C2′H (J=2.5 Hz).



Scheme 7. Reagents and conditions: (a) NaOMe, MeOH, rt (100%); (b) **44**, TMSOTf, MS4A, CH_2Cl_2, −78 °C (93%); (c) TFAA, Py, CH_2Cl_2, 0 °C→rt (**46**: 51%, **47**: 26%, **48**: 13%); (d) CCl_3CN.

On treatment of **45** with TFAA in CH_2Cl_2 in the presence of pyridine, the Pummerer rearrangement proceeded to give alcohol **46** in 51% yield after aqueous work-up. Product **46** was observed as a 72:28 inseparable anomeric mixture. Stereochemistry of the anomeric position could not be assigned due to spectral crowding in the ^1H NMR spectrum. Contrary to our expectation, the regioselectivity of the rearrangement for **45** was a little lower than that in previous experiments. *endo*-Olefin **47** and *exo*-olefin **48** produced through the rearrangement to the C5 position were isolated in 26 and 13% yields, respectively. Probably, the bulky thioglucose moiety attached to the C6 position might affect the reaction courses of the rearrangement (Scheme 8).

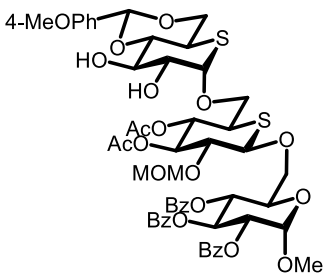
We failed in all attempts to convert the alcohol **46** into trichloroacetimidate **49** which is required for extension of the sugar chain. As mentioned in Section 2.4, the acetonide group of **46** was expected to strain the angle ∠S−C1−C2 to be around 115°. This distortion might accelerate the detachment of the imidate group which might result in the decomposition of **49** on silica gel. The acetonide group of **46** was removed in order to overcome this problem. Treatment of the tautomeric mixture of **46** with catalytic hydrochloric acid in methanol gave an anomeric mixture of triols α-**50** and β-**50**. The ^1H NMR spectrum of this mixture indicated that α-**50** was the predominant isomer α-**50**/β-**50**=67:33). Interestingly, these anomers could be separated by silica gel column chromatography, although isomers of anomeric



Scheme 8. Reagents and conditions: (a) cat. HCl, MeOH, rt (α-**50**:61%, β-**50**:30%); (b) Ac_2O, Py, rt (α-**51**: 83%, β-**51**: 89%); (c) H_2NNH_2−AcOH, DMF, rt [(α-**52**: 79%, β-**52**: 7.8%) from α-**51**, (α-**52**: 69%, β-**52**: 7.0%) from β-**51**]; (d) cat. DBU, CCl_3CN, CH_2Cl_2, 0 °C→rt (77%); (e) **54**, TMSOTf, MS4A, CH_2Cl_2, −78 °C, then separation (α-**55**: 57%, β-**55**: 19%); (f) DDQ, CH_2Cl_2, H_2O, rt (α-**56**: 70%, β-**56**: 44%, **57**: 26%); (g) (i) NaOMe, MeOH, rt (α-isomer: 79%, β-isomer: 100%), (ii) cat. HCl, MeOH, rt (α-**58**: 78%, β-**58**: 40%).

alcohols were usually inseparable because of tautomerization. Both isomers could be converted to the triacetate without remarkable isomerization, giving α-**51** and β-**51** both as almost pure forms in 83 and 89% yields, respectively. However, on cleavage of the C1 acetyl group by hydrazine acetate the isomerization resumed. Thus, both α-**51** and β-**51** gave a separable mixture of alcohols α-**52** and β-**52** (91:9 ratio). As expected, α-**52** could successfully be converted into trichloroacetimidate **53** in 77% yield as a single isomer by treating with trichloroacetonitrile in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU).[43] The stereochemistry of **53** was confirmed to be α-configuration by observing the characteristic coupling constant (J=3.4 Hz) for the C1 proton (6.42 ppm).

Glycosidation of alcohol **54** with the imidate **53** took place smoothly by treating with catalytic TMSOTf in the presence of molecular sieves 4 Å, giving adducts α-**55** and β-**55** (75:25 ratio) in 76% yield. These isomers could be separated by medium-pressure silica gel column chromatography. MOM group at the C2 position may partially contribute to the β-glycosidation. Finally, all protective groups of **55** were removed. Treatment of α-**55** with 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ) smoothly oxidized MPM ethers.[44] These conditions constructed 4-methoxybenzylidene acetal at the C4″ and C6″ positions to give α-**56** in 70% yield without oxidizing the sulfide moieties.[8] The same oxidation converted β-**55** into the benzylidene acetal β-**56** in 44% yield along with tetraol **57** (26%). It was found that the benzylidene moiety of β-**56** was gradually cleaved in $CDCl_3$, affording **57** in quantitative yield. Then, the benzoyl and acetyl protective groups of both α-**56** and **57** were removed under basic conditions, providing the corresponding nonanols in 79 and 100%, respectively. In the last step, treatment with catalytic hydrochloric acid in methanol cleaved the MOM ether and 4-methoxybenzylidene to provide α-**58** in 78%. The same treatment removed the MOM ether to afford β-**58** in 40% yield. The final products



β-56

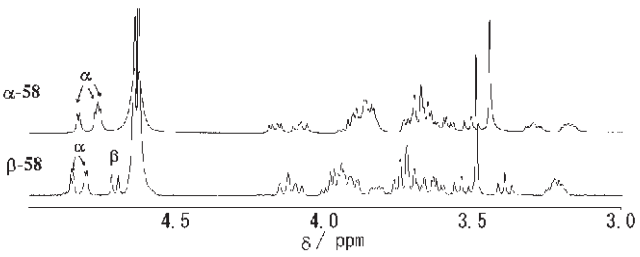


Figure 4. ^{1}H NMR spectra (homo decoupling) of isomaltotriose α-**58** and its epimer β-**58** in D_2O.

α-**58** and β-**58** were purified by medium-pressure ODS column chromatography.

The ^{1}H NMR spectra of α-**58** and its epimer β-**58** are shown in Figure 4. The signal patterns of the anomeric protons of α-**58** revealed that all of the glucosyl bonds of α-**58** are linked by α-configuration, while one of the signals corresponding to the anomeric protons of β-**58** indicates the existence of β-glycoside linkage. The HSQC and mass spectra also supported those structures.

3. Conclusion

We have succeeded in developing stereoselective Pummerer rearrangement reaction of 1-deoxy-5-thio-D-glucopyranose derivatives carrying an acetonide group at the C3 and C4 positions. Experiments employing deuterium-labelled derivatives revealed the details of the rearrangement. Further, this reaction was applied to the preparation of sulfur-substituted isomaltotriose α-**58** and its epimer β-**58**. Those carbomimetics are expected to be an effective antagonist for glycosidases. Enzymatic experiments employing them are under investigation in our laboratories.

4. Experimental

4.1. General

Melting points were determined with a Yanako MP-J3 micro melting point apparatus and were uncorrected. Optical rotations were measured on a HORIBA SEPA300 high-sensitivity polarimeter. For some compounds, consisted of a mixture of diastereomers, the optical rotations were not measured. ^{1}H NMR spectra were measured on a JEOL ALPHA 400 spectrometer (400 MHz). The chemical shifts are expressed in ppm downfield from the signal of trimethylsilane used as an internal standard in the case of $CDCl_3$. When another solvent was employed, the remained proton signals in deuterosolvents C_6HD_5 (7.15 ppm), CHD_2OD (3.30 ppm), or HDO (4.63 ppm) were used as the internal standards. Splitting patterns are designated as s (singlet), d (doublet), t (triplet), m (multiplet), and br (broad). ^{13}C NMR spectra were recorded also on a JEOL ALPHA 400 spectrometer (100 MHz). The isotope ^{13}C in the solvents were used as the internal standard ($^{13}CDCl_3$; 77.0 ppm, $^{13}C_6D_6$; 128.0 ppm, or $^{13}CD_3OD$; 49.5 ppm). For ^{13}C NMR spectra measured in D_2O, default offset was employed and did not perform correction. Assignments of the signals are according to the numbering based on IUPAC nomenclature if not mentioned. For carbohydrate derivatives numbering based on carbohydrate nomenclature is employed. IR spectra were obtained with a HORIBA FT-720 Fourier transform infrared spectrometer on a KBr cell. Measurements of electron impact, field desorption, fast atom bombardment, and electrospray ionization mass spectra (EI-MS, FD-MS, FAB-MS, and ESI-MS, respectively) were performed on a JEOL JMS AX500 or JEOL JMS AX102A spectrometers in Hokkaido University. When MS spectra were measured by negative mode, 'negative mode' is mentioned. MS analysis for unstable compounds such as glycosyl imidates was not performed.

Analytical and preparative thin-layer chromatographies were carried out using precoated silica gel plates, Merck silica gel 60F_{254} (Art. 1.05715). Silica gel used for column chromatography was Merck silica gel 60 (Art. 1.07734). Medium-pressure column chromatographies were performed employing Yamazene ULTRA PACK SI-40B or Merck Lobar® LiChroprep® RP-18 Type A) equipped with FMI LAB PUMP RP-SY. All reactions were carried out under N_2 or Ar atmosphere using dried solvents except for aqueous conditions. Dichloromethane and tetrahydropyran were freshly distilled from diphosphorus pentoxide and benzophenone-ketyl, respectively. Molecular sieves 4 Å were finely powdered and activated (200 °C in vacuo for 1 h) before use.

4.1.1. 6-*O*-Benzoyl-1,5-dideoxy-3,4-*O*-isopropylidene-2-*O*-methoxymethyl-5-thio-D-glucopyranose (5). A mixture of 6-*O*-benzoyl-1,5-dideoxy-3,4-*O*-isopropylidene-5-thio-D-glucopyranose (**4**) (317 mg, 978 μmol), prepared according to Merrer et al.,[20] MOMCl (150 mg, 2.45 mmol), and $^{i}Pr_2NEt$ (420 μL, 4.39 mmol) in CH_2Cl_2 (500 μL) was stirred at room temperature for 3 h. The mixture was poured into saturated aqueous $NaHCO_3$ and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue by silica gel column chromatography (hexane/EtOAc=85:15) gave **5** (311 mg, 86%) as an oil. $[\alpha]_D^{24}=-13.3$ (*c* 1.60, $CHCl_3$), IR (film) δ 2985, 2935, 2890, 1725, 1270, 1150, 1105, 1040, 715 cm^{-1}, ^1H NMR ($CDCl_3$) δ 1.41 (6H, s, C(C*H*$_3$)$_2$), 2.68 (1H, dd, *J*=10.3, 13.2 Hz, C1*H*H), 2.92 (1H, dd, *J*=4.4, 13.2 Hz, C1*H*H), 3.34 (1H, t, *J*=10.3 Hz, C3*H*), 3.38 (3H, s, C*H*$_3$O), 3.40 (1H, dt, *J*=3.9, 8.8 Hz, C5*H*), 3.66 (1H, dd, *J*=8.8, 10.3 Hz, C4*H*), 3.93 (1H, dt, *J*=4.4, 10.3 Hz, C2*H*), 4.31 (1H, dd, *J*=8.8, 11.7 Hz, C6*H*), 4.73 (1H, d, *J*=6.9 Hz, OCH*H*O), 4.75 (1H, dd, *J*=3.9, 11.7 Hz, C6*H*), 4.85 (1H, d, *J*=6.9 Hz, OCH*H*O), 7.43–8.03 (5H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 26.7, 26.9 (C(*C*H$_3$)$_2$), 31.9 (*C*1), 44.6 (*C*5), 55.5 (*C*H$_3$O), 63.9 (*C*6), 77.0 (*C*2), 77.9 (*C*4), 82.0 (*C*3), 96.2 (O*C*H$_2$O), 109.4 (*C*(CH$_3$)$_2$), 128.4, 129.7, 129.8, 133.1 (aromatic carbons), 166.0 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=353 (7.0, $[M-CH_3]^+$), 306 (7.0, $M-[MOMOH]^+$), 105 (100, $PhCO^+$), FD-MS (rel. int., %) *m*/*z*=368 (100, M^+), 353 (41, $[M-CH_3]^+$), EI-HRMS; found: *m*/*z* 353.1046. Calcd for $C_{17}H_{21}O_5S$: $[M-CH_3]^+$, 353.1059.

4.1.2. 2,6-*O*-Dibenzoyl-1,5-dideoxy-3,4-*O*-isopropylidene-5-thio-D-glucopyranose (6). A mixture of **4** (69.4 mg, 214 μmol), BzCl (49.7 μL, 427 μmol), and pyridine (43.2 μL, 534 μmol) in CH_2Cl_2 (1.0 mL) was stirred at room temperature for 20 h. The mixture was poured into H_2O and extracted with EtOAc. The combined extracts were washed with brine dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue by silica gel column chromatography (hexane/EtOAc=88:12) gave **6** (86.9 mg, 95%) as an oil. $[\alpha]_D^{23}=+81.3$ (*c* 1.18, $CHCl_3$), IR (film) 2985, 1725, 1270, 1110, 1070, 1025, 710 cm^{-1}, ^1H NMR ($CDCl_3$) δ 1.44, 1.45 (each 3H, s, C(C*H*$_3$)$_2$), 2.76 (1H, dd, *J*=10.3, 13.7 Hz, C1*H*H), 3.10 (1H, dd, *J*=4.9, 13.7 Hz, C1*H*H), 3.49 (1H, ddd, *J*=3.5, 7.8, 8.8 Hz, C5*H*), 3.61 (1H, t, *J*=10.3 Hz, C3*H*), 3.84 (1H, dd, *J*=8.8, 10.3 Hz, C4*H*), 4.38 (1H, dd, *J*=7.8, 11.8 Hz, C6*H*), 4.81 (1H, dd, *J*=3.5, 11.8 Hz, C6*H*), 5.34 (1H, dt, *J*=4.9, 10.3 Hz, C2*H*), 7.45–8.06 (10H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 26.7, 26.8 (C(*C*H$_3$)$_2$), 30.7 (*C*1), 44.8 (*C*5), 63.8 (*C*6), 73.4 (*C*2), 78.1 (*C*4), 80.3 (*C*3), 109.9 (*C*(CH$_3$)$_2$), 128.35, 128.41, 129.68, 129.72, 129.72, 129.9, 133.2, 133.3 (aromatic carbons), 165.6, 166.1 (Ph*C*O×2), EI-MS (rel. int., %) *m*/*z*=413 (6.0, $[M-CH_3]^+$), 306 (2.4, $M-[PhCOOH]^+$), 248 (10, $[M-PhCOOH-acetone]^+$), 105 (100, $PhCO^+$), FD-MS (rel. int., %) *m*/*z*=428 (63, M^+), 413 (100, $[M-CH_3]^+$), EI-HRMS; found: *m*/*z* 413.1024. Calcd for $C_{22}H_{21}O_6S$: $[M-CH_3]^+$, 413.1059.

4.2. 2,3,4,6-*O*-Tetrabenzoyl-1,5-dideoxy-5-thio-D-glucopyranose (7)

4.2.1. Removal of the acetonide. A solution of **4** (224 mg, 690 μmol) in methanol (10 mL) was stirred with concentrated aqueous HCl (10 μL) at room temperature for 3 h. After the mixture was neutralized with Et_3N, the mixture was concentrated in vacuo. Silica gel column chromatography of the residue (CH_2Cl_2/acetone=70:30) gave the corresponding triol (166 mg, 85%) as a solid. Analytical sample was obtained by recrystallization from hexane/EtOAc (50:50) to give colorless needles. mp=143–144 °C, $[\alpha]_D^{24}=+46.5$ (*c* 0.95, MeOH), IR (KBr) 3400, 2920, 1712, 1275, 1065, 710 cm^{-1}, ^1H NMR (CD_3OD), δ 2.58–2.68 (2H, C1*H*$_2$), 3.09 (1H, ddd, *J*=3.4, 6.4, 10.2 Hz, C5*H*), 3.14 (1H, t, *J*=8.8 Hz, C3*H*), 3.54 (1H, dd, *J*=8.8, 10.2 Hz, C4*H*), 3.61 (1H, dt, *J*=5.3, 8.8 Hz, C2*H*), 4.48 (1H, dd, *J*=6.4, 11.7 Hz, C6*H*), 4.70 (1H, dd, *J*=3.4, 11.7 Hz, C6*H*), 7.47–8.02 (5H, aromatic protons), ^{13}C NMR (CD_3OD), 33.4 (*C*1), 47.3 (*C*5), 65.1 (*C*6), 74.8 (*C*2), 75.4 (*C*4), 80.7 (*C*3), 129.6, 130.6, 131.2, 134.3 (aromatic carbons), 167.8 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=284 (0.2, M^+), 266 (4.4, $[M-H_2O]^+$), 248 (3.8, $[M-2H_2O]^+$), 162 (68, $[M-PhCOOH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m*/*z* 284.0765. Calcd for $C_{13}H_{16}O_5S$: M^+, 284.0718.

4.2.2. Benzoylation giving 7. A mixture of the product (166 mg, 584 μmol) and BzCl (340 μL, 2.92 mmol) was stirred in pyridine (7.0 mL) at room temperature for 24 h. The mixture was poured into saturated aqueous $NaHCO_3$ and extracted with ether. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=85: 15) gave **7** (347 mg, 100%) as a colorless oil. $[\alpha]_D^{24}=+31.1$ (*c* 0.88, $CHCl_3$), IR (film) 1730, 1450, 1270, 1105, 710 cm^{-1}, ^1H NMR ($CDCl_3$) δ 2.86 (1H, dd, *J*=10.8, 13.2 Hz, C1*H*H), 3.09 (1H, dd, *J*=4.4, 13.2 Hz, C1*H*H), 3.53 (1H, ddd, *J*=3.9, 5.8, 9.7 Hz, C5*H*), 4.36 (1H, dd, *J*=5.8, 11.7 Hz, C6*H*), 4.54 (1H, dd, *J*=3.9, 11.7 Hz, C6*H*), 5.42 (1H, ddd, *J*=4.4, 9.7, 10.8 Hz, C2*H*), 5.64 (1H, t, *J*=9.7 Hz, C3*H*), 5.76 (1H, t, *J*=9.7 Hz, C4*H*), 7.10–7.92 (20H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 30.1 (*C*1), 44.7 (*C*5), 62.6 (*C*6), 73.0 (*C*4), 73.4 (*C*2), 74.6 (*C*3), 128.1, 128.25, 128.33, 128.33, 128.8, 128.9, 129.1, 129.4, 129.5, 129.65, 129.65, 129.72, 133.0, 133.1, 133.2, 133.3 (aromatic carbons), 165.3, 165.4, 165.8, 165.9 (Ph*C*O×4), FD-MS (rel. int., %) *m*/*z*=596 (7.0, M^+), 595 (13, $[M-H]^+$), 122 (100, $PCOOH^+$), FD-HRMS; found: *m*/*z* 596.1485. Calcd for $C_{34}H_{28}O_8S$: M^+, 596.1505.

4.2.3. 6-*O*-Benzoyl-1,5-dideoxy-2,3-*O*-isopropylidene-5-thio-D-glucopyranose (8a). A solution of **4** (326 mg,

1.00 mmol) in acetone (5.0 mL) was stirred with *p*-TsOH·H_2O (10 mg, 52.6 μmol) at room temperature for 2.5 h. After the mixture was neutralized by the addition of Et_3N, the mixture was concentrated in vacuo. Medium pressured silica gel column chromatography of the residue (hexane/EtOAc=90:10) gave **8a** (196 mg, 60%) and recovered **4** (105 mg, 32%) both as oils. The ^{1}H NMR spectrum of recovered **4** was identical with the authentic sample.

4.2.4. Physical data for 8a. $[\alpha]_D^{21}$=+55.8 (*c* 0.90, $CHCl_3$), IR (film) 2985, 2920, 1720, 1270, 1115, 715 cm^{-1}, ^{1}H NMR (C_6D_6) δ 1.32, 1.33 (each 3H, s, C(CH_3)$_2$), 2.43 (2H, C1H_2), 2.88 (1H, dt, *J*=4.4, 9.2 Hz, C5*H*), 3.05 (1H, t, *J*=9.2 Hz, C4*H*), 3.66 (1H, dt, *J*=6.8, 9.2 Hz, C2*H*), 3.75 (1H, t, *J*=9.2 Hz, C3*H*), 4.65 (2H, d, *J*=4.4 Hz, C6H_2), 7.02–8.16 (5H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.9, 27.0 (C(*C*H_3)$_2$), 30.6 (*C*1), 47.0 (*C*5), 63.1 (*C*6), 72.6 (*C*4), 77.1 (*C*2), 84.2 (*C*3), 109.6 (*C*(CH$_3$)$_2$), 128.5, 128.6, 130.1, 130.4, 133.1 (aromatic carbons), 166.4 (Ph*C*O), EI-MS (rel. int., %), 309(3.5, [M−CH_3]$^+$), 267 (1.4, [M−isobutene]$^+$), 105 (51, PhCO$^+$), EI-HRMS; found: *m*/*z* 309.0788. Calcd for $C_{15}H_{17}O_5S$: [M−CH_3]$^+$, 309.0797.

4.2.5. 4-Acetoxy-6-*O*-benzoyl-1,5-dideoxy-2,3-*O*-isopropylidene-5-thio-D-glucopyranose (8b). A solution of **8a** (340 mg, 1.05 mmol) in a mixture of Ac_2O (3.0 mL) and pyridine (6.0 mL) was stirred at room temperature for 1.5 h. After concentration, silica gel column chromatography of the residue (hexane/EtOAc=80:20) gave **8b** (384 mg, 100%) as a colorless oil. $[\alpha]_D^{21}$=+51.8 (*c* 6.2, $CHCl_3$), IR (film) 2985, 1725, 1375, 1240, 1115, 1025, 715 cm^{-1}, ^{1}H NMR (C_6D_6) δ 1.26, 1.29 (each 3H, s, C(CH_3)$_2$), 1.64 (3H, s, CH_3CO), 2.37 (2H, C1H_2), 2.98 (1H, ddd, *J*=3.4, 6.3, 9.7 Hz, C5*H*), 3.17 (1H, dd, *J*=8.8, 9.7 Hz, C3*H*), 3.75 (1H, dt, *J*=7.3, 8.8 Hz, C2*H*), 4.30 (1H, dd, *J*=6.3, 12.2 Hz, C6*H*H), 4.58 (1H, dd, *J*=3.4, 12.2 Hz, C6*H*H), 5.55 (1H, t, *J*=9.7 Hz, C4*H*), 7.05–8.23 (5H, aromatic protons), ^{13}C NMR (C_6D_6) 20.3 (*C*H_3CO), 26.87, 26.88 (C(*C*H_3)$_2$), 30.5 (*C*1), 45.2 (*C*5), 62.4 (*C*6), 72.6 (*C*4), 77.5 (*C*2), 81.9 (*C*3), 109.9 (*C*(CH$_3$)$_2$), 128.5, 128.6, 130.1, 130.4, 133.1 (aromatic carbons), 165.9, 169.2 (Ph*C*O×2), EI-MS (rel. int., %) *m*/*z*=351 (3.7, [M−CH_3]$^+$), 306 (0.7, [M−AcOH]$^+$), 184 (34, [M−AcOH−PhCOOH]$^+$), 126 (57, [M−AcOH−PhCOOH−acetone]$^+$), 105 (100, PhCO$^+$), EI-HRMS; found: *m*/*z* 351.0902. Calcd for $C_{17}H_{19}O_6S$: [M−CH_3]$^+$, 351.0902.

4.3. 6-*O*-Benzoyl-1,5-dideoxy-3,4-*O*-isopropylidene-2-*O*-methoxymethyl-5-thio-D-glucopyranose (*R*)-*S*-oxide (*eq*-9) and its (*S*)-isomer (*ax*-9)

4.3.1. Preparation. A mixture of **5** (658 mg, 1.79 mmol) and *m*CPBA (70% purity, 439 mg, 1.79 mmol) was stirred in CH_2Cl_2 (5.0 mL) at −20 °C for 30 min. The mixture was poured into 5% aqueous sodium thiosulfate solution and extracted with CH_2Cl_2. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (benzene/EtOAc=70:30) gave *eq*-**9** (302 mg, 44%) and *ax*-**9** (298 mg, 43%) both as colorless oils.

4.3.2. Physical data for *eq*-9. $[\alpha]_D^{23}$=−45.3 (*c* 1.35, $CHCl_3$), (film) 2980, 2925, 1725, 1270, 1150, 1105, 1050, 1035, 710 cm^{-1}, ^{1}H NMR (C_6D_6) δ 1.14, 1.21 (each 3H, s, C(CH_3)$_2$), 2.69 (1H, ddd, *J*=3.0, 4.4, 11.7 Hz, C5*H*), 2.75 (1H, dd, *J*=9.3, 12.2 Hz, C1*H*H), 3.08 (3H, s, CH_3O), 3.19 (1H, dd, *J*=9.3, 11.7 Hz, C4*H*), 3.32 (1H, dd, *J*=4.4, 12.2 Hz, C1*H*H), 3.58 (1H, t, *J*=9.3 Hz, C3*H*), 3.63 (1H, dt, *J*=4.4, 9.3 Hz, C2*H*), 4.36, 4.64 (each 1H, d, *J*=6.8 Hz, OCH_2O), 4.72 (1H, dd, *J*=4.4, 12.2 Hz, C6*H*H), 4.93 (1H, dd, *J*=3.0, 12,2 Hz, C6*H*H), 7.03–7.12 (3H, aromatic protons), 8.17–8.19 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.71, 26.74 (C(*C*H_3)$_2$), 55.2 (*C*H3O), 55.4 (*C*1), 59.6 (*C*6), 64.2 (*C*5), 69.2 (*C*2), 71.0 (*C*4), 82.4 (*C*3), 95.6 (O*C*H_2O), 111.7 (*C*(CH$_3$)$_2$), 128.6, 130.0, 130.5, 133.1 (aromatic carbons), 165.7 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=385 (trace, M+H$^+$), 369 (5.7, [M−CH_3]$^+$), 322 (1.0 [M−MOMOH]$^+$), 105 (100, PhCO$^+$), FD-MS (rel. int., %) *m*/*z*=385 (18, [M+H]$^+$), 369 (100, [M−CH_3]$^+$), EI-HRMS; found: *m*/*z* 369.0986. Calcd for $C_{17}H_{21}O_7S$: [M−CH_3]$^+$, 369.1008.

4.3.3. Physical data for *ax*-9. $[\alpha]_D^{23}$=+15.1 (*c* 0.98, $CHCl_3$), IR (film) 2985, 2935, 2895, 1725, 1270, 1235, 1150, 1105, 1060, 1035, 715 cm^{-1}, ^{1}H NMR (C_6D_6) δ 1.21, 1.30 (each 3H, s, C(CH_3)$_2$), 1.69 (1H, dd, *J*=11.2, 14.6 Hz, C1*H*H), 2.53 (1H, dt, *J*=4.4, 11.7 Hz, C5*H*), 3.10 (3H, s, CH_3O), 3.20 (1H, dd, *J*=4.4, 14.6 Hz, C1*H*H), 3.29 (1H, t, *J*=9.3 Hz, C3*H*), 4.25 (1H, dd, *J*=9.3, 11.7 Hz, C4*H*), 4.45 (1H, d, *J*=6.4 Hz, OCH*H*O), 4.62 (1H, ddd, *J*=4.4, 9.3, 11.2 Hz, C2*H*), 4.68 (1H, dd, *J*=10.8, 11.7 Hz, C6*H*H), 4.74 (1H, d, *J*=6.4 Hz, OCH*H*O), 5.14 (1H, dd, *J*=4.4, 10.8 Hz, C6*H*H), 7.03–7.13 (3H, aromatic protons), 8.15–8.17 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.6, 26.9 (C(*C*H_3)$_2$), 50.6 (*C*1), 55.2 (*C*H3O), 58.8 (*C*5), 59.9 (*C*6), 71.1 (*C*2), 72.7 (*C*4), 82.3 (*C*3), 96.1 (O*C*H_2O), 109.9 (*C*(CH$_3$)$_2$), 128.5, 128.6, 130.1, 130.3, 133.2 (aromatic carbons), 165.8 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=369 (4.0, [M−CH_3]$^+$), 262 (13, [M−PhCOOH]$^+$), 105 (100, PhCO$^+$), FD-MS (rel. int., %) *m*/*z*=384 (31, M$^+$), 369 (100, [M−CH_3]$^+$), EI-HRMS; found: *m*/*z* 369.1024. Calcd for $C_{17}H_{21}O_7S$: [M−CH_3]$^+$, 369.1008.

4.4. 2,6-*O*-Dibenzoyl-1,5-dideoxy-3,4-*O*-isopropylidene-5-thio-D-glucopyranose (*R*)-*S*-oxide (*eq*-10) and its (*S*)-isomer (*ax*-10)

Treatment of **6** (25.0 mg, 58.3 μmol) in a similar manner as described in Section 4.3.1 gave *eq*-**10** (14.1 mg, 55%) *ax*-**10** (9.5 mg, 36.7%) after silica gel column chromatography (benzene/EtOAc=95:5).

4.4.1. Physical data for *eq*-10. $[\alpha]_D^{24}$=+41.9 (*c* 0.80, $CHCl_3$), IR (film) 3445, 2985, 1725, 1270, 1265, 1105, 1045, 705 cm^{-1}, ^{1}H NMR (C_6D_6) δ 1.13, 1.22 (each 3H, s, C(CH_3)$_2$), 2.66 (1H, dd, *J*=9.3, 12.7 Hz, C1*H*H), 2.82 (1H, ddd, *J*=3.4, 5.4, 11.2 Hz, C5*H*), 3.24 (1H, dd, *J*=4.9, 12.7 Hz, C1*H*H), 3.25 (1H, dd, *J*=9.3, 11.2 Hz, C4*H*), 3.99 (1H, t, *J*=9.3 Hz, C3*H*), 4.62 (1H, dd, *J*=5.4, 12.2 Hz, C6*H*H), 4.82 (1H, dd, *J*=3.4, 12.2 Hz, C6*H*H), 5.32 (1H, dt, *J*=4.9, 9.3 Hz, C2*H*), 6.98–8.16 (10H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.6, 26.8 (C(*C*H_3)$_2$), 53.4 (*C*1), 60.0 (*C*6), 64.8 (*C*5), 67.8 (*C*2), 71.4 (*C*4), 79.8 (*C*3), 112.1 (*C*(CH$_3$)$_2$), 128.55, 128.60, 129.9, 130.0, 130.1, 130.3, 133.2, 133.4 (aromatic carbons), 165.2, 166.7 (Ph*C*O×2), EI-MS (rel. int., %) *m*/*z*=445 (0.3, [M+H]$^+$), 429 (0.8,

$[M-CH_3]^+$), 264 (0.6, $[M-PhCOOH-acetone]^+$), 105 (100, $PhCO^+$), EI-HRMS; found *m/z* 445.1291. Calcd for $C_{23}H_{25}O_7S$: $[M+H]^+$, 445.1321.

4.4.2. Physical data for *ax*-10. $[\alpha]_D^{24}=+46.1$ (*c* 0.92, $CHCl_3$), IR (film) 3735, 2920, 2850, 1720, 1270, 1105, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.15, 1.30 (each 3H, s, $C(CH_3)_2$), 1.58 (1H, dd, *J*=10.7, 14.1 Hz, C1*H*H), 2.65 (1H, dt, *J*=4.4, 11.2 Hz, C5*H*), 3.33 (1H, dd, *J*=3.9, 14.1 Hz, C1*H*H), 3.48 (1H, dd, *J*=9.8, 10.7 Hz, C3*H*), 4.39 (1H, dd, *J*=9.8, 11.2 Hz, C4*H*), 4.68 (1H, d, *J*=11.2, 12.7 Hz, C6*H*H), 5.16 (1H, dd, *J*=4.4, 12.7 Hz, C6*H*H), 6.13 (1H, dt, *J*=3.9, 10.7 Hz, C2*H*), 6.99–8.16 (10H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.4, 27.0 ($C(CH_3)_2$), 49.2 (*C*1), 59.2 (*C*5), 59.9 (*C*6), 69.3 (*C*2), 72.9 (*C*4), 80.3 (*C*3), 110.5 ($C(CH_3)_2$), 128.5, 128.7, 130.0, 130.0, 130.1, 130.2, 133.2, 133.3 (aromatic carbons), 165.0, 165.8 (Ph*C*O×2), EI-MS (rel. int., %) *m/z*=444 (0.7, M+), 429 (1.0, $[M-CH_3]^+$), 322 (1.8, $[M-PhCOOH]^+$), 264 (5.5, $[M-PhCOOH-acetone]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 444.1214. Calcd for $C_{23}H_{24}O_7S$: M^+, 444.1243.

4.5. 2,3,4,6-*O*-Tetrabenzoyl-1,5-dideoxy-5-thio-D-glucopyranose (*R*)-*S*-oxide (*eq*-11) and its (*S*)-isomer (*ax*-11)

Treatment of **7** (347 mg, 581 μmol) in a similar manner as described in Section 4.3.1 gave *eq*-**11** (170 mg, 48%) and *ax*-**11** (172 mg, 48%) after silica gel column chromatography (benzene/EtOAc=90: 10).

4.5.1. Physical data for *eq*-11. $[\alpha]_D^{24}=+45.2$ (*c* 0.80, $CHCl_3$), IR (film) 1730, 1265, 1105, 710 cm^{-1}, ^1H NMR ($CDCl_3$) δ 3.22 (1H, t, *J*=11.8 Hz, C1*H*H), 3.49 (1H, dt, *J*=2.5, 11.7 Hz, C5*H*), 4.02 (1H, dd, *J*=3.9, 11.8 Hz, C1*H*H), 4.68 (1H, dd, *J*=2.5, 12.7 Hz, C6*H*H), 4.86 (1H, dd, *J*=2.5, 12.7 Hz, C6*H*H), 5.45 (1H, ddd, *J*=3.9, 9.8, 11.8 Hz, C2*H*), 5.79 (1H, dd, *J*=9.8, 11.7 Hz, C4*H*), 5.90 (1H, t, *J*=9.8 Hz, C3*H*), 7.10–7.5 (20H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 52.6 (*C*1), 56.6 (*C*6), 64.8 (*C*4), 65.3 (*C*2), 65.7 (*C*5), 74.0 (*C*3), 128.1, 128.2, 128.27, 128.32, 128.36, 128.39, 128.44, 128.5, 129.6, 129.7, 129.8, 129.8, 133.3, 133.4, 133.6, 133.7 (aromatic carbons), 164.7, 165.1, 165.5, 165.6 (Ph*C*O×4), EI-MS (rel. int., %) *m/z*=612 (0.6, M^+), 490 (3.3, $[M-PhCOOH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 612.1484. Calcd for $C_{34}H_{28}O_9S$: M^+, 612.1454.

4.5.2. Physical data for *ax*-11. $[\alpha]_D^{23}=+12.8$ (*c* 1.0, $CHCl_3$), IR (film) 1730, 1270, 1105, 710 cm^{-1}, ^1H NMR ($CDCl_3$) δ 2.72 (1H, dd, *J*=11.7, 14.2 Hz, C1*H*H), 3.38 (1H, ddd, *J*=4.9, 9.3, 11.2 Hz, C5*H*), 3.85 (1H, dd, *J*=3.9, 14.2 Hz, C1*H*H), 4.64 (1H, dd, *J*=9.3, 12.2 Hz, C6*H*H), 4.78 (1H, dd, *J*=4.9, 12.2 Hz, C6*H*H), 5.90 (1H, t, *J*=9.8 Hz, C3*H*), 6.10 (1H, ddd, *J*=3.9, 9.8, 11.7 Hz, C2*H*), 6.23 (1H, dd, *J*=9.8, 11.2 Hz, C4*H*), 7.11–7.88 (20H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 47.4 (*C*1), 59.0 (*C*5), 60.0 (*C*6), 67.3 (*C*2), 67.9 (*C*4), 73.8 (*C*3), 128.2, 128.3, 128.38, 128.38, 128.42, 128.5, 128.8, 129.0, 129.6, 129.7, 129.76, 129.80, 133.3, 133.41, 133.43, 133.5 (aromatic carbons), 164.9, 165.2, 165.8, 165.9 (Ph*C*O×4), EI-MS (rel. int., %) *m/z*=612 (3.1, M^+), 490 (1.4, $[M-PhCOOH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 612.1484. Calcd for $C_{34}H_{28}O_9S$: M^+, 612.1454.

4.6. 4-Acetoxy-6-*O*-benzoyl-1,5-dideoxy-2,3-*O*-isopropylidene-5-thio-D-glucopyranose (*R*)-*S*-oxide (*eq*-12) and its (*S*)-isomer (*ax*-12)

Treatment of **8b** (74.4 mg, 203 μmol) in a similar manner as described in Section 4.3.1 gave *eq*-**12** (42.6 mg, 55%) and *ax*-**12** (28.7 mg, 37%) after silica gel column chromatography (benzene/EtOAc=80:20). Analytical sample for *ax*-**12** was obtained by recrystallization from hexane/EtOAc (50:50) giving plates.

4.6.1. Physical data for *eq*-12. $[\alpha]_D^{21}=-16.2$ (*c* 0.39, $CHCl_3$), IR (film) 2985, 1730, 1375, 1240, 1100, 1025, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.12, 1.21 (each 3H, s, $C(CH_3)_2$), 1.51 (3H, s, CH_3CO), 2.55 (1H, dd, *J*=10.7, 13.2 Hz, C1*H*H), 2.73 (1H, ddd, *J*=3.0, 4.8, 11.2 Hz, C5*H*), 3.05 (1H, ddd, *J*=2.4, 9.3, 13.2 Hz, C2*H*), 3.28 (1H, dd, *J*=2.4, 10.7 Hz, C1*H*H), 3.44 (1H, t, *J*=9.3 Hz, C3*H*), 4.68 (1H, dd, *J*=3.0, 12.7 Hz, C6*H*H), 4.93 (1H, dd, *J*=4.8, 12.7 Hz, C6*H*H), 5.50 (1H, dd, *J*=9.3, 11.2 Hz, C4*H*), 7.03–8.21 (5H, aromatic protons), ^{13}C NMR (C_6D_6) δ 20.1 (CH_3CO), 26.5, 26.7 ($C(CH_3)_2$), 52.2 (*C*1), 56.5 (*C*6), 65.0 (*C*4), 67.0 (*C*5), 69.1 (*C*2), 81.6 (*C*5), 111.8 ($C(CH_3)_2$), 127.9, 128.6, 130.1, 133.2 (aromatic carbons), 165.8, 168.6 (CH_3CO and Ph*C*O), EI-MS (rel. int., %) *m/z*=383 (0.4, $[M+H]^+$), 367 (1.5, $[M-CH_3]^+$), 322 (1.2, $[M-AcOH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 383.1168. Calcd for $C_{18}H_{23}O_7S$: M^+, 383.1164.

4.6.2. Physical data for *ax*-12. Mp=181–182 °C, $[\alpha]_D^{21}=+142$ (*c* 1.78, $CHCl_3$), IR (KBr) 2985, 1730, 1375, 1240, 1100, 1050, 715 cm^{-1}, ^1H NMR (C_6D_6) δ 1.18, 1.29 (each 3H, s, $C(CH_3)_2$), 1.63 (1H, dd, *J*=12.2, 13.2 Hz, C1*H*H), 1.65 (3H, s, CH_3CO), 2.52 (1H, dt, *J*=3.9, 9.8 Hz, C5*H*), 3.03 (1H, dd, *J*=3.4, 13.2 Hz, C1*H*H), 3.30 (1H, t, *J*=9.8 Hz, C3*H*), 4.61 (1H, ddd, *J*=3.4, 9.8, 12.2 Hz, C2*H*), 4.68 (1H, dd, *J*=9.8, 11.7 Hz, C6*H*H), 4.86 (1H, dd, *J*=3.9, 11.7 Hz, C6*H*H), 6.00 (1H, t, *J*=9.8 Hz, C4*H*), 7.04–8.16 (5H, aromatic protons), ^{13}C NMR (C_6D_6) δ 20.2 (CH_3CO), 26.5, 27.0 ($C(CH_3)_2$), 48.1 (*C*1), 59.8 (*C*6), 60.6 (*C*5), 68.9 (*C*4), 71.6 (*C*2), 81.1 (*C*3), 110.6 ($C(CH_3)_2$), 128.7, 130.05, 130.11, 133.4 (aromatic carbons), 165.9, 169.2 (CH_3CO and Ph*C*O), EI-MS (rel. int., %) *m/z*=383 (2.1, $[M+H]^+$), 367 (0.7, $[M-CH_3]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 383.1208. Calcd for $C_{18}H_{23}O_7S$: $[M+H]^+$, 383.1164.

4.7. Pummerer rearrangement of 1,5-dideoxy-5-thio-D-glucopyranose derivatives

4.7.1. Typical conditions. To a mixture of sulfoxide and pyridine (10 equiv.) in CH_2Cl_2, TFAA (5 equiv.) was added at 0 °C. After 5 min, the cooling bath was removed and the mixture was stirred at room temperature until TLC indicated that the starting sulfoxide was disappeared. After addition of MeOH to decompose excess TFAA, the mixture was poured into H_2O and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue gave products.

4.7.2. Reaction of *eq*-9 (run 1). Treatment of *eq*-**9** (15.0 mg, 39.3 μmol) in a similar manner as described in Section 4.7.1 gave **15** (14 mg) as an oil after silica gel

column chromatography (benzene/EtOAc=90: 10). Since **15** was observed as broad spot on silica gel TLC, accurate yield of **15** could not be obtained. Analytical sample was prepared from a part of the fractions. The yield of this reaction was estimated to be 66% after acetylation of the alcohol moiety as described in Section 4.12. Physical data for **15** are follows; $[\alpha]_D^{23}$=+32.9 (*c* 1.56, $CHCl_3$), IR (film) 3440, 2930, 1725, 1275, 1235, 1155, 1106, 1070, 1030, 715 cm^{-1}. The ^1H NMR spectrum of this sample showed that it consists of the two tautomers arising from the C1 anomeric position (α-anomer/β-anomer=90:10). Assignments of the signals for the main isomer and some for the minor isomer are described. ^1H NMR (C_6D_6, *a*=0.9, *b*=0.1) δ 1.27, 1.29 (each 3H×*a*, s, C(CH_3)$_2$ (α-isomer)), 3.11 (3H×*a*, s, CH_3O (α-isomer)), 3.16 (3H×*b*, s, CH_3O (β-isomer)), 3.46 (1H×*b*, t, *J*=9.3 Hz, C4*H* (β-isomer)), 3.65 (1H×*a*, ddd, *J*=2.9, 6.8, 10.8 Hz, C5*H* (α-isomer)), 3.71 (1H×*a*, dd, *J*=8.3, 10.8 Hz, C4*H* (α-isomer)), 3.92 (1H×*a*, dd, *J*=3.0, 10.3 Hz, C2*H* (α-isomer)), 4.07 (1H×*a*, dd, *J*=8.3, 10.3 Hz, C3*H* (α-isomer)), 4.35 (1H×*b*, dd, *J*=7.3, 11.2 Hz, C6*H*H (β-isomer)), 4.41 (1H×*a*, dd, *J*=7.3, 11.7 Hz, C6*H*H (α-isomer)), 4.47 (1H×*a*, d, *J*=6.8 Hz, OC*H*HO (α-isomer)), 4.63 (1H×*b*, d, *J*=6.4 Hz, OC*H*HO (β-isomer)), 4.70 (1H×*a*, d, *J*=6.8 Hz, OC*H*HO (α-isomer)), 4.74 (1H×*b*, d, *J*=6.4 Hz, OC*H*HO (β-isomer)), 4.78 (1H×*a*, dd, *J*=2.9, 11.7 Hz, C6*H*H (α-isomer)), 4.80 (1H×*a*, d, *J*=3.0 Hz, C1*H* (α-isomer)), 7.00–7.05 (3H, aromatic protons), 8.17 (2H, aromatic protons), ^{13}C NMR (C_6D_6, signals for only major isomer are described.) δ 26.7, 27.1 (C(CH_3)$_2$), 42.2 (*C*5), 55.3 (CH_3O), 63.7 (*C*6), 75.0 (*C*1), 77.5 (*C*3), 78.9 (*C*4), 79.5 (*C*2), 95.9 (OCH_2O), 109.4 ($C(CH_3)_2$), 128.5, 130.1, 130.5, 133.0 (aromatic carbons), 165.9 (Ph*C*O), FD-MS (rel. int., %) *m*/*z*=384 (75, M^+), 369 (100, $[M-CH_3]^+$), FD-HRMS; found: *m*/*z* 384.1261. Calcd for $C_{18}H_{24}O_7S$: M^+, 384.1243.

4.7.3. Reaction of *ax*-9 (run 2). Treatment of *ax*-**9** (46.6 mg, 121 μmol) in a similar manner as described in Section 4.7.1 gave **15** (60 mg), and trace amount of **19**. The yield of **15** was estimated to be 84% after acetylation. The ^1H NMR spectrum of **15** was identical with that prepared from *eq*-**9**.

4.7.4. Reaction of *eq*-10 in CH_2Cl_2 (run 3). Treatment of *eq*-**10** (30.1 mg, 67.7 μmol) in a similar manner as described in Section 4.7.1 gave **20** (22.3 mg, 55%) and trace amount of **21**, **22**, and **23** after column chromatography (hexane/EtOAc=80:20).

4.7.5. Physical data for 20. $[\alpha]_D^{24}$=+99.9 (*c* 3.02, $CHCl_3$), IR (film) 3440, 2985, 2980, 1720, 1270, 1110, 1070, 710 cm^{-1}. The ^1H NMR spectrum of this sample showed that it consists of the two tautomers arising from the C1 anomeric position (α-anomer/β-anomer=91:9). Assignments of the signals for the main isomer and some for the minor isomer are described. ^1H NMR (C_6D_6, *a*=0.9, *b*=0.1) δ 1.28, 1.30 (each 3H×*a*, s, C(CH_3)$_2$ (α-isomer)), 1.24, 1.25 (each 3H×*b*, s, C(CH_3)$_2$ (β-isomer)), 3.66 (1H×*a*, ddd, *J*=3.9, 7.8, 11.2 Hz, C5*H* (α-isomer)), 3.82 (1H×*a*, dd, *J*=8.8, 10.8 Hz, C4*H* (α-isomer)), 4.08 (1H×*b*, t, *J*=8.0 Hz, C4*H* (β-isomer)), 4.38 (1H×*a*, dd, *J*=7.3, 11.7 Hz, C6*H*H (α-isomer)), 4.40 (1H×*a*, dd, *J*=8.8, 10.8 Hz, C3*H* (α-isomer)), 4.78 (1H×*a*, dd, *J*=3.9, 11.7 Hz, C6*H*H (α-isomer)), 5.11 (1H×*a*, br, C1*H* (α-isomer)), 5.54 (1H×*a*, dd, *J*=2.9, 10.7 Hz, C2*H* (α-isomer)), 5.65 (1H×*b*, dd, *J*=8.0, 10.3 Hz, C2*H* (β-isomer)), 6.96–7.15 (6H, aromatic protons), 8.16–8.20 (4H, aromatic protons), ^{13}C NMR (C_6D_6, signals for only major isomer are described.) δ 26.7, 27.0 (C(CH_3)$_2$), 42.2 (*C*5), 63.6 (*C*6), 74.1 (*C*1), 75.8 (*C*3), 76.5 (*C*2), 79.2 (*C*4), 109.9 ($C(CH_3)_2$), 128.46, 128.54, 130.1, 130.2, 130.3, 130.4, 133.1, 133.2 (aromatic carbons), 165.91, 169.94 (Ph*C*O×2), EI-MS (rel. int., %) *m*/*z*=445 (0.8, MH^+), 429 (1.8, $[M-CH_3]^+$), 369 (1.2, [M−acetone−OH]$^+$), 322 (4.5, [M−PhCOOH]$^+$), 105 (100, $PhCO^+$), FD-MS *m*/*z*=445 (76, MH^+), 429 (100, $[M-CH_3]^+$), EI-HRMS; found: *m*/*z* 429.1012. Calcd for $C_{22}H_{21}O_7S$: $[M-CH_3]^+$, 429.1008.

4.8. Reaction of *ax*-10 in CH_2Cl_2 (run 4)

Treatment of *ax*-**10** (45.0 mg, 101 μmol) in a similar manner as described in Section 4.7.1 gave **20** (22.3 mg, 55%) and trace amount of **21**, **22**, and **23** after column chromatography. The ^1H NMR spectrum of **20** was identical with that prepared from *eq*-**10**.

4.9. Reaction of *eq*-10 in pyridine (run 5)

Treatment of *eq*-**10** (40.5 mg, 91.2 μmol) with TFAA (30 μL, 212 μmol) in pyridine (1.5 mL) in a similar manner as described in Section 4.7.1 gave **20** (26.5 mg, 66%) after column chromatography. The ^1H NMR spectrum of **20** was identical with that reported in Section 4.7.4.

4.10. Reaction of *ax*-10 in pyridine (run 6)

Treatment of *ax*-**10** (60.1 mg, 135 μmol) in a similar manner as described in Section 4.7.1 gave **20** (39.7 mg, 65%) after column chromatography. The ^1H NMR spectrum of **20** was identical with that reported in Section 4.7.5.

4.11. Reaction of *eq*-11 (run 7)

Treatment of *eq*-**11** (74 mg, 121 μmol) in a similar manner as described in Section 4.7.1 gave **24** (4.2 mg, 5.7%), **25** (4.8 mg, 4.0%), **26** (37.0 mg, 50%), **27** (5.6 mg, 8.9%), and **28** (11.5 mg, 8.9%) after column chromatography. The structure of **27** was estimated from the results that treatment of **27** with Et_3N in MeOH at room temperature produced **26**.

4.11.1. Physical data for α-24. $[\alpha]_D^{22}$=+90.3 (*c* 0.56, $CHCl_3$), IR (film) 3450, 1730, 1270, 1105, 710 cm^{-1}, ^1H NMR ($CDCl_3$), δ 2.51 (1H, d, *J*=2.0 Hz, O*H*), 4.00 (1H, ddd, *J*=3.9, 4.8, 10.7 Hz, C5*H*), 4.42 (1H, dd, *J*=4.8, 11.7 Hz, C6*H*H), 4.50 (1H, dd, *J*=3.9, 11.7 Hz, C6*H*H), 5.35 (1H, dd, *J*=2.0, 2.9 Hz, C1*H*), 5.49 (1H, dd, *J*=2.9, 10.3 Hz, C2*H*), 5.82 (1H, t, *J*=10.7 Hz, C4*H*), 6.13 (1H, dd, *J*=10.3, 10.7 Hz, C3*H*), 7.08–7.45 (12H, aromatic protons), 7.66–7.92 (8H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 39.5 (*C*5), 62.2 (*C*6), 70.8 (*C*3), 71.9 (*C*1), 73.1(*C*4), 75.9 (*C*2), 128.18, 128.23, 128.3, 128.40, 128.42, 128.9, 129.0, 129.4, 129.5, 129.8, 129.81, 129.84, 133.0, 133.2, 133.3, 133.4 (aromatic carbons), 165.4, 165.7, 165.8, 166.0 (PhCO×4), FD-MS (rel. int., %) *m*/*z*=612 (19, M^+), 611

(34, $[M-H]^+$), 491 (36, $[MH-PhCOOH]^+$), 122 (99, $PhCOOH^+$), 105 (100, $PhCO^+$), FD-HRMS; found: *m/z* 612.1470. Calcd for $C_{34}H_{28}O_9S$: M^+, 612.1454.

4.11.2. Physical data for β-24. $[\alpha]_D^{22}=+36.4$ (*c* 0.44, $CHCl_3$), IR (film) 3440, 1730, 1270, 1105, 710 cm^{-1}, ^1H NMR ($CDCl_3$), δ 3.20 (1H, d, *J*=8.3 Hz, O*H*), 3.67 (1H, ddd, *J*=4.4, 5.9, 10.7 Hz, C5*H*), 4.49 (1H, dd, *J*=5.9, 11.7 Hz, C6*H*H), 4.63 (1H, dd, *J*=4.4, 11.7 Hz, C6*H*H), 5.18 (1H, t, *J*=8.3 Hz, C1*H*), 5.64 (1H, t, *J*=8.3 Hz, C2*H*), 5.77 (1H, dd, *J*=8.3, 10.7 Hz, C3*H*), 5.87 (1H, t, *J*=10.7 Hz, C4*H*), 7.15–7.55 (12H, aromatic protons), 7.75–8.05 (8H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 41.9 (*C*5), 62.5 (*C*6), 72.62 (*C*3), 72.67 (*C*4), 74.9 (*C*1), 77.5 (*C*2), 128.2, 128.35, 128.41, 128.43, 128.65, 128.69, 128.7, 129.3, 129.6, 129.75, 129.81, 129.9, 133.24, 133.24, 133.4, 133.7 (aromatic carbons), 165.3, 165.7, 166.0, 167.3 (PhCO×4), FD-MS (rel. int., %) *m/z*=612 (20, M^+), 611 (31, $[M-H]^+$), 491 (25, $[MH-PhCOOH]^+$), 122 (56, $PhCOOH^+$), 105 (100, $PhCO^+$), FD-HRMS; found: *m/z* 612.1429. Calcd for $C_{34}H_{28}O_9S$: M^+, 612.1454.

4.11.3. Physical data for 25. $[\alpha]_D^{22}=-66.3$ (*c* 0.41, $CHCl_3$), IR (film) 1730, 1260, 1095, 710 cm^{-1}, ^1H NMR ($CDCl_3$), δ 2.98 (1H, dd, *J*=9.8, 12.7 Hz, C1*H*H), 3.14 (1H, dd, *J*=4.4, 12.7 Hz, C1*H*H), 5.50 (1H, ddd, *J*=4.4, 7.8, 9.8 Hz, C2*H*), 5.63 (1H, t, *J*=7.8 Hz, C3*H*), 6.03 (1H, dd, *J*=1.5, 7.8 Hz, C4*H*), 7.20–7.53 (12H, aromatic protons), 7.76 (1H, d, *J*=1.5 Hz, C6*H*), 7.77–8.04 (8H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 29.9 (*C*1), 71.6 (*C*4), 72.2 (*C*2), 73.7 (*C*3), 112.9 (*C*5), 128.33, 128.35, 128.4, 128.5, 128.7, 128.8, 129.0, 129.2, 129.7, 129.8, 129.9, 130.3, 133.3, 133.4, 133.5, 134.0 (aromatic carbons), 135.9 (*C*6), 162.6, 165.0, 165.47, 165.49 (Ph*C*O×4), FD-MS (rel. int., %) *m/z*=594 (100, M^+), 105 (36, $PhCO^+$), FD-HRMS; found: *m/z* 594.1381. Calcd for $C_{34}H_{26}O_8S$: M^+, 594.1348.

4.11.4. Physical data for 26. $[\alpha]_D^{23}=-19.6$ (*c* 6.08, $CHCl_3$), IR (film), 1730, 1270, 1110, 710 cm^{-1}, ^1H NMR ($CDCl_3$), 2.98 (1H, dd, *J*=4.4, 13.2 Hz, C1*H*H), 3.24 (1H, dd, *J*=11.2, 13.2 Hz, C1*H*H), 3.91 (1H, s, O*H*), 4.46, 4.56 (each 1H, d, *J*=11.7 Hz, C6*H*H), 5.45 (1H, ddd, *J*=4.4, 9.7, 11.2 Hz, C2*H*), 5.86 (1H, d, *J*=9.7 Hz, C4*H*), 6.15 (1H, t, *J*=9.7 Hz, C3*H*), 7.08–7.45 (12H, aromatic protons), 7.65–7.90 (8H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 26.3 (*C*1), 68.3 (*C*6), 71.6 (*C*3), 73.9 (*C*2), 75.4 (*C*4), 82.7 (*C*5), 128.1, 128.3, 128.4, 128.5, 128.6, 128.8, 129.0, 129.2, 129.5, 129.8, 129.86, 129.93, 133.0, 133.3, 133.4, 133.6 (aromatic carbons), 165.6, 165.7, 165.8, 166.9 (Ph*C*O×4), EI-MS (rel. int., %) *m/z*=594 (0.1, M^+), 472 (0.3, $[M-PhCOOH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 594.1322. Calcd for $C_{34}H_{26}O_8S$: M^+, 594.1348.

4.11.5. Physical data for 28. $[\alpha]_D^{23}=+153.1$ (*c* 1.96, $CHCl_3$), IR (film), 1725, 1260, 1095, 705 cm^{-1}, ^1H NMR (C_6D_6), 2.94 (1H, dd, *J*=5.4, 13.7 Hz, C1*H*H), 2.99 (1H, dd, *J*=3.0, 13.7 Hz, C1*H*H), 5.03, 5.08 (each 1H, d, *J*=13.1 Hz, C6*H*H), 5.58 (1H, ddd, *J*=3.0, 4.4, 5.4 Hz, C2*H*), 6.43 (1H, d, *J*=4.4 Hz, C3*H*), 6.85–7.10 (12H, aromatic protons), 7.94–8.28 (8H, aromatic protons), ^{13}C NMR (C_6D_6, Signals for C4 and C5 could not be detected probably due to those relaxation time) δ 27.0 (*C*1), 61.0 (*C*6), 68.1 (*C*3), 68.6 (*C*2), 128.1, 128.3, 128.4, 128.5, 128.6, 128.8, 129.0, 129.2, 129.5, 129.8, 129.9, 129.93, 132.96, 133.3, 133.4, 133.6 (aromatic carbons), 165.61, 165.65, 165.8, 166.9 (Ph*C*O×4), FD-MS (rel. int., %) *m/z*=612 (100, M^+), 595 (19, $[M-OH]^+$), FD-HRMS; found: *m/z* 612.1478. Calcd for $C_{34}H_{28}O_9S$: M^+, 612.1454.

4.11.6. Reaction of *ax*-11 (run 8). Treatment of *eq*-**11** (106 mg, 173 μmol) in a similar manner as described in Section 4.7.1 gave **24** (2.8 mg, 2.7%), **25** (0.3 mg, 0.3%), **26** (43.5 mg, 41%), **27** (5.6 mg, 5.6%), and **28** (9.1 mg, 8.1%) after column chromatography.

4.11.7. Reaction of *eq*-12 (run 9). Treatment of *eq*-**12** (52.2 mg, 136 μmol) in a similar manner as described in Section 4.7.1 gave **30** (6.9 mg, 14%), **31** (20.9 mg, 40%) and **32** (1.1 mg, 1.7%), after column chromatography. The structure of **32** was estimated by production of **30** and **31** by treating **32** with Et_3N in MeOH at room temperature.

4.11.8. Physical data for 30. $[\alpha]_D^{22}=-159.2$ (*c* 0.68, $CHCl_3$), IR (film) 3450, 2985, 2935, 1740, 1225, 1135, 1080, 1045, 705 cm^{-1}, ^1H NMR (C_6D_6) δ 1.27, 1.29 (each 3H, s, $C(CH_3)_2$), 1.64 (3H, s, CH_3CO), 2.45 (2H, C1H_2), 3.40 (1H, dd, *J*=8.8, 10.2 Hz, C3*H*), 3.78 (1H, dt, *J*=5.8, 8.8 Hz, C2*H*), 6.05 (1H, dd, *J*=2.0, 10.2 Hz, C4*H*), 6.99–8.19 (5H, aromatic protons), 7.93 (1H, d, *J*=2.0 Hz, C6*H*), ^{13}C NMR (C_6D_6) δ 20.1 (CH_3CO), 26.8, 26.9 ($C(CH_3)_2$), 31.7 (*C*1), 72.8 (*C*4), 76.6 (*C*2), 81.1 (*C*3), 109.9 ($C(CH_3)_2$), 114.8 (*C*5), 128.7, 130.5, 133.8, 134.9 (aromatic carbons), 162.7, 169.0 (CH_3CO and Ph*C*O), EI-MS (rel. int., %) *m/z*=364 (0.5, M^+), 349 (0.5, $[M-CH_3]^+$), 289 (1.3, $[M-acetone-OH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 364.0972. Calcd for $C_{18}H_{20}O_6S$: M^+, 364.0981.

4.11.9. Physical data for 31. Mp=145–146 °C (needles, from hexane/EtOAc (50:50)), $[\alpha]_D^{23}=-17.7$ (*c* 0.73, $CHCl_3$), IR (KBr) 3430, 1640, 1295, 1225, 715 cm^{-1}, ^1H NMR ($CDCl_3$) δ 1.41, 1.43 (each 3H, s, $C(CH_3)_2$), 2.14 (3H, s, CH_3CO), 2.82 (1H, dd, *J*=3.4, 11.7 Hz, C1*H*H), 3.04 (1H, dd, *J*=10.7, 11.7 Hz, C1*H*H), 3.34 (1H, s, O*H*), 3.91 (1H, dt, *J*=3,4, 10.7 Hz, C2*H*), 3.98 (1H, t, *J*=10.7 Hz, C3*H*), 4.36, 4.52 (each 1H, d, *J*=11.7 Hz, C6*H*H), 5.43 (1H, d, *J*=10.7 Hz, C4*H*), 7.44–8.04 (5H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 20.9, (CH_3CO), 26.6, 27.0 ($C(CH_3)_2$), 28.1 (*C*1), 67.9 (*C*6), 74.5 (*C*4), 76.9 (*C*3), 77.7 (*C*2), 84.2 (*C*5), 110.2 ($C(CH_3)_2$), 128.6, 129.0, 130.0, 133.6 (aromatic carbons), 166.6, 170.0 (CH_3CO and Ph*C*O), EI-MS (rel. int., %) *m/z*=367 (0.8, $[M-CH_3]^+$), 307 (1.6, $[M-acetone-OH]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m/z* 367.0831. Calcd for $C_{17}H_{19}O_7S$: $[M-CH_3]^+$, 367.0852.

4.12. Acetylation of 15 giving 1-acetoxy-6-*O*-benzoyl-1,5-dideoxy-3,4-*O*-isopropylidene-2-*O*-methoxymetyl-5-thio-α-D-glucopyranose (α-16) and its β-isomer (β-16)

A mixture of the Pummerer product obtained in Section 4.7.2 and Ac_2O (0.2 mL, excess) was stirred in pyridine (1.0 mL) at room temperature for 30 min. After concentration in vacuo, silica gel column chromatography (benzene/EtOAc=90:10) gave a diastereomeric mixture of

16 (11 mg, 66%). Analytical sample was further purified by preparative silica gel column chromatography (benzene/EtOAc=80:20).

4.12.1. Physical data for α-16. $[\alpha]_D^{23}$=+91.5 (*c* 0.94, $CHCl_3$), IR (film) 2985, 2895, 1750, 1725, 1270, 1215, 1110, 1045, 1020, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.28, 1.29 (each 3H, s, C(C*H*$_3$)$_2$), 1.64 (3H, s, C*H*$_3$CO), 3.20 (3H, s, C*H*$_3$O), 3.63 (2H, C4*H*, C5*H*), 4.01 (1H, dd, *J*=7.8, 10.2 Hz, C3*H*), 4.10 (1H, dd, *J*=3.4, 10.2 Hz, C2*H*), 4.32 (1H, dd, *J*=7.3, 11.7 Hz, C6*H*H), 4.56, 4.71 (each 1H, d, *J*=6.8 Hz, OC*H*HO), 4.80 (1H, dd, *J*=3.4, 11.7 Hz, C6*H*H), 6.40 (1H, d, *J*=3.4 Hz, C1*H*), 6.97–7.08 (3H, aromatic protons), 8.12 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ 20.5 (*C*H$_3$CO), 26.7, 27.0 (C(C*H*$_3$)$_2$), 43.1 (*C*5), 55.4 (*C*H$_3$O), 63.9 (*C*6), 73.5 (*C*1), 77.5 (*C*2), 78.0 (*C*3), 78.6 (*C*4), 95.8 (O*C*H$_2$O), 109.6 (*C*(CH$_3$)$_2$), 128.5, 130.0, 130.3, 133.1 (aromatic carbons), 165.8, 168.8 (CH$_3$*C*O and Ph*C*O), EI-MS (rel. int., %) *m*/*z*=411 (10, $[M-CH_3]^+$), 304 (18, $[M-PhCOOH]^+$), 105 (100, $PhCO^+$), FD-MS (rel. int., %) *m*/*z*=426 (16, M^+), 411 (100, $[M-CH_3]^+$), EI-HRMS; found *m*/*z* 411.1121. Calcd for $C_{19}H_{23}O_8S$: $[M-CH_3]^+$, 411.1114.

4.12.2. Physical data for β-16. $[\alpha]_D^{23}$=−43.4 (*c* 1.45, $CHCl_3$), IR (film) 2930, 2895, 1755, 1725, 1270, 1215, 1105, 1030, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.25, 1.27 (each 3H, s, C(C*H*$_3$)$_2$), 1.52 (3H, s, C*H*$_3$CO), 3.15 (1H, ddd, *J*=5.8, 7.3, 9.2 Hz, C5*H*), 3.21 (3H, s, C*H*$_3$O), 3.59 (1H, t, *J*=9.2 Hz, C3*H*), 3.88 (1H, t, *J*=9.2 Hz, C4*H*), 4.23 (1H, dd, *J*=4.8, 9.2 Hz, C2*H*), 4.30 (1H, dd, *J*=7.8, 11.2 Hz, C6*H*H), 4.66 (1H, d, *J*=6.9 Hz, OC*H*HO), 4.69 (1H, dd, *J*=5.4, 11.2 Hz, C6*H*H), 4.82 (1H, d, *J*=6.9 Hz, OC*H*HO), 6.91 (1H, d, *J*=4.8 Hz, C1*H*), 7.01–7.10 (3H, aromatic protons), 8.16 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ 20.2 (*C*H$_3$CO), 26.9, 27.1 (C(*C*H$_3$)$_2$), 43.9 (C5), 55.4(*C*H$_3$O), 65.4 (*C*6), 76.1 (*C*4), 76.3 (*C*1), 79.5(*C*2), 81.7(*C*3), 95.9 (O*C*H$_2$O), 110.9(*C*(CH$_3$)$_2$), 128.5, 130.0, 130.5, 133.0 (aromatic carbons), 165.9, 168.2 (CH$_3$*C*O and Ph*C*O), EI-MS (rel. int., %) *m*/*z*=411 (7.0, $[M-CH_3]^+$), 364 (6.3, $[M-MOMOH]^+$), 304 (39, $[M-PhCOOH]^+$), 105 (100, $PhCO^+$), FD-MS (rel. int., %) *m*/*z*=426 (29, M^+), 411 (100, $[M-CH_3]^+$), EI-HRMS; found: *m*/*z* 411.1137. Calcd for $C_{19}H_{23}O_8S$: $[M-CH_3]^+$, 411.1114.

4.13. 1,2,3,4,6-*O*-Pentabenzoyl-5-deoxy-5-thio-D-glucopyranose (17)

4.13.1. Preparation from 16. A solution of **16** (22.0 mg, 51.5 μmol) in 50% aqueous TFA was stirred at room temperature for 3 h. After concentration in vacuo, the residue was stirred with BzCl (59.9 μL, 258 μmol) in pyridine (300 μL) at room temperature for 15 h. The mixture was poured into saturated aqueous $NaHCO_3$ solution and extracted with Et_2O. The combined extracts were washed with 2 M aqueous HCl and brine successively, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=85:15) gave **17** (25.0 mg, 63% two steps) as an anomeric mixture (α/β=80:20). $[\alpha]_D^{19}$=+161 (*c* 3.40, $CHCl_3$), IR (film) 1730, 1265, 1105, 1070, 705 cm^{-1}, The ^1H NMR spectrum of this sample showed that it consists of the two isomers arising from the C1 anomeric position (α/β=80:20). Assignments of the signals for the main isomer and some for the minor isomer are described. ^1H NMR ($CDCl_3$, *a*=0.8, *b*=0.2) δ 3.76 (1H×*b*, dt, *J*=9.3, 5.4 Hz, C5*H* (minor)), 3.96 (1H×*a*, dt, *J*=3.9, 10.3 Hz, C5*H* (major)), 4.45, 4.50 (each 1H×*a*, dd, *J*=3.9, 12.2 Hz, C6*H*H (major)), 4.63 (1H×*b*, dd, *J*=4.9, 11.7 Hz, C6*H*H (minor)), 5.75 (1H×*a*, dd, *J*=3.0, 10.3 Hz, C2*H* (major)), 5.95 (1H×*a*, t, *J*=10.3 Hz, C4*H* (major)), 6.19 (1H×*a*, t, *J*=10.3 Hz, C3*H* (major)), 6.36 (1H×*b*, d, *J*=7.8 Hz, C1*H* (minor)), 6.54 (1H×*a*, d, *J*=3.0 Hz, C1*H* (major)), 7.08–7.56 (15H, aromatic protons), 7.67–8.06 (10H, aromatic protons), EI-MS (rel. int. %) *m*/*z*=595 (0.1, $[M-PhCOO]^+$), 472 (1.9, $[M-2\times PhCOOH]^+$), 350 (21, $[M-3\times PhCOOH]^+$), 105 (100, $PhCO^+$), EI-HRMS; Found *m*/*z* 595.1426. Calcd for $C_{34}H_{27}O_8S$: $[M-PhCOO]^+$, 595.1427.

4.13.2. Preparation from 18. A mixture of 1,2,3,4,6-*O*-pentaacetyl-5-deoxy-5-thio-D-glucopyranose **18** (72.0 mg, 177 μmol), prepared according to Driguez et al.,[30] and NaOMe (57.4 mg, 1.06 mmol) in MeOH (1.0 mL) was stirred at room temperature for 12 h. After concentration in vacuo, the residue was diluted with H_2O (2.0 mL), then was passed through ion exchange resin (DOWEX 50W-X4, H^+ form). The eluate was concentrated in vacuo. The residue was stirred with BzCl (0.2 mL, 1.72 mmol) in pyridine (0.5 mL) at room temperature for 12 h. The mixture was poured into saturated aqueous $NaHCO_3$ solution and extracted with EtOAc. The combined extracts were washed with 2 M aqueous HCl and brine successively, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=85:15) gave **17** (85.0 mg, 67% in two steps) as an anomeric mixture (α/β=90:10). The ^1H NMR spectrum of this sample was identical except for the isomeric ratio with that of described in Section 4.13.1.

4.14. 6-*O*-*tert*-Butyldimethylsilyl-3,4-*O*-isopropylidene-2,5-*O*-bis(methanesulfonyl)-D-mannose (34)

4.14.1. Protection of terminal alcohols as the bis-TBDMS ether. A mixture of 3,4-*O*-isopropylidene-D-mannitol (**33**) (102.6 mg, 462 μmol), TBDMSCl (139.2 mg, 923 μmol), and Et_3N (0.19 mL, 1.39 mmol) in DMF (3 mL) was stirred at room temperature for 30 min. The mixture was poured into saturated aqueous $NaHCO_3$ solution and extracted with Et_2O. The combined extracts were washed with saturated aqueous NH_4Cl and brine successively, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=92:8) gave the corresponding 1,6-bisTBDMS ether (208 mg, 100%) as an oil. $[\alpha]_D^{23}$=+15.3 (*c* 1.14, $CHCl_3$), IR (film) 3400, 2925, 2855, 1465, 1375, 1255, 1215, 1070 cm^{-1}, ^1H NMR ($CDCl_3$) δ 0.04 (12H, s, Si(C*H*$_3$)$_2$×2), 0.85 (18H, s, SiC(C*H*$_3$)$_3$×2), 1.30 (6H, s, C(C*H*$_3$)$_2$), 3.37 (2H, br, O*H*×2), 3.58 (2H, C2*H*, C5*H*), 3.65 (2H, dd, *J*=5.8, 10.2 Hz, C1H*H*, C6H*H*), 3.83 (4H, C1H*H*, C3*H*, C4*H*, C6H*H*), ^{13}C NMR ($CDCl_3$) δ −5.4 (Si(*C*H$_3$)$_2$×2), 18.3 (Si*C*(CH$_3$)$_3$×2), 25.8 (SiC(*C*H$_3$)$_3$×2), 26.9 (C(*C*H$_3$)$_2$), 64.4 (*C*1, *C*6) 73.0 (*C*2, *C*5), 79.3 (*C*3, *C*4), 109.1 (*C*(CH$_3$)$_2$), EI-MS (rel. int., %) *m*/*z*=451 (0.8, $[M+H]^+$), 449 (0.1, $[M-H]^+$), 435 (7.0, $[M-CH_3]^+$), 393 (9.7, $[M-{}^tBu]^+$), 335 (19, $[M-{}^tBu-acetone]^+$), 117 (100), EI-HRMS; found: *m*/*z* 435.2627. Calcd $[M-CH_3]^+$ for $C_{20}H_{43}O_6Si_2$: $[M-CH_3]^+$, 435.2598.

4.14.2. Mesylation of the 2,5-hydroxy groups. A mixture of the product (1.76 g, 3.90 mmol), MsCl (604 μL, 7.81 mmol), and Et_3N (1.63 mL, 11.7 mmol) in CH_2Cl_2 (15 mL) was stirred at 0 °C for 30 min. The mixture was poured into H_2O, and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=95:5) gave the corresponding 2,5-bismesylate ether (2.35 mg, 99%) as an oil. $[\alpha]_D^{17}$=+17.3 (*c* 1.58, $CHCl_3$), IR (film) 2925, 2850, 1700, 1105, 1025 cm^{-1}, ^1H NMR ($CDCl_3$) δ 0.00 (12H, s, Si(C*H*$_3$)$_2$×2), 0.81 (18H, s, SiC(C*H*$_3$)$_3$×2), 1.32 (6H, s, C(C*H*$_3$)$_2$), 3.01 (6H, s, SO_2CH_3×2), 3.75 (2H, dd, *J*=6.3, 11.7 Hz, C1H*H*, C6H*H*), 3.92 (2H, dd, *J*=3.4, 11.7 Hz, C1H*H*, C6H*H*), 4.26 (2H, C3*H*, C4*H*), 4.62 (2H, C2*H*, C5*H*), ^{13}C NMR ($CDCl_3$) δ −5.6 (Si(*C*H$_3$)$_2$×2), 18.2 (Si*C*(CH$_3$)$_3$×2), 25.7 (SiC(*C*H$_3$)$_3$×2), 26.9 (C(*C*H$_3$)$_2$), 38.6 (SO_2CH_3×2), 62.4 (*C*1, *C*6) 76.1 (*C*2, *C*5), 82.3 (*C*3, *C*4), 110.9 (*C*(CH$_3$)$_2$), EI-MS (rel. int., %) *m*/*z*=591 (20, $[M-CH_3]^+$), 549 (8.2, $[M-{}^tBu]^+$), 153 (100), EI-HRMS; found: *m*/*z* 591.2138. Calcd for $C_{22}H_{47}O_{10}Si_2S_2$: $[M-CH_3]^+$, 591.2149.

4.14.3. Desilylation giving the corresponding monoalcohol. A mixture of the product obtained in Section 4.14.2 (1.84 g, 3.04 mmol), 1 M TBAF in THF (3.0 mL, 3.0 mmol), and AcOH (364 mg, 2.80 mmol) in THF (20 mL) was stirred at 0 °C for 3 h. The mixture was poured into H_2O, and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=75:25) gave the corresponding monoalcohol (1.01 mg, 67%), recovered bis-TBDMS ether (368 mg, 20%), and the diol (115 mg, 10%) as an oil. The ^1H NMR spectra of the recovered bis-TBDMS ether and diol were identical with those of the authentic samples.

4.14.4. Physical data for the mono-TBDMS ether. $[\alpha]_D^{17}$=+22.0 (*c* 0.48, $CHCl_3$), IR (film) 3510, 2935, 2855, 1340, 1175 cm^{-1}, ^1H NMR ($CDCl_3$) δ −0.01, 0.00 (each 3H, s, Si(C*H*$_3$)$_2$), 0.82 (9H, s, SiC(C*H*$_3$)$_3$), 1.31, 1.32 (each 3H, s, C(C*H*$_3$)$_2$), 3.02, 3.04 (each 3H, s, SO_2CH_3), 3.74 (1H, dd, *J*=4.4, 11.7 Hz, C6H*H*), 3.76 (1H, dd, *J*=3.0, 11.7 Hz, C1*H*H), 3.87 (1H, dd, *J*=3.4, 11.7 Hz, C1*H*H), 3.92 (1H, dd, *J*=3.4, 11.7 Hz, C6H*H*), 4.16 (1H, t, *J*=6.8 Hz, C3*H*), 4.31 (1H, t, *J*=6.8 Hz, C4*H*), 4.60 (1H, ddd, *J*=3.0, 3.4, 6.8 Hz, C2*H*), 4.66 (1H, ddd, *J*=3.4, 4.4, 6.8 Hz, C5*H*), ^{13}C NMR ($CDCl_3$) δ −5.2 (Si(*C*H$_3$)$_2$), 18.6 (Si*C*(CH$_3$)$_3$), 26.1 (SiC(*C*H$_3$)$_3$), 27.2, 27.3, (C(*C*H$_3$)$_2$), 38.8, 39.1 (SO_2CH_3×2), 61.9, 62.9 (*C*1, *C*6) 76.4,77.0 (*C*2, *C*5), 82.0, 83.2 (*C*3, *C*4), 111.5 (*C*(CH$_3$)$_2$), EI-MS (rel. int., %) *m*/*z*=477 (14, $[M-CH_3]^+$), 435 (3.1, $[M-{}^tBu]^+$), 153 (100), EI-HRMS; found: *m*/*z* 477.1295. Calcd for $C_{16}H_{33}O_{10}SiS_2$: $[M-CH_3]^+$, 477.1284.

4.14.5. Oxidation giving 34. A mixture of the mono-TBDMS ether obtained in Section 4.14.3 (59.2 mg, 120 μmol) and Dess-Martin reagent (76.4 mg, 180 μmol) in CH_2Cl_2 (2 mL) was stirred at room temperature for 3 h. The mixture was poured into a mixture of saturated aqueous $NaHCO_3$ and 10% $Na_2S_2O_3$ (10 mL) and extracted with ether. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=85:15) gave **34** (59.1 mg, 100%). ^1H NMR ($CDCl_3$) δ 0.09 (6H, s, Si(C*H*$_3$)$_2$), 0.89 (9H, s, SiC(C*H*$_3$)$_3$), 1.40, 1.43 (each 3H, s, C(C*H*$_3$)$_2$), 3.13, 3.19 (each 3H, s, SO_2CH_3), 3.83 (1H, dd, *J*=6.8, 12.2 Hz, C6H*H*), 3.97 (1H, dd, *J*=2.9, 12.2 Hz, C6*H*H), 4.30 (1H, t, *J*=7.8 Hz, C4*H*), 4.56 (1H, dd, *J*=2.9, 7.8 Hz, C3*H*), 4.67 (1H, ddd, *J*=2.9, 6.8, 7.8 Hz, C5*H*), 4.98 (1H, d, *J*=2.9 Hz, C2*H*), 9.66 (1H, s, C1*H*). This sample was subjected to the next step without further purification.

4.14.6. (1*R*)-6-*O*-*tert*-Butyldimethylsilyl-1-deuterio-3,4-*O*-isopropylidene-2,5-*O*-bis(methanesulfonyl)-D-mannitol (35). To a mixture of **34** (689 mg, 1.40 mmol) and Ce (III) chloride (1.04 g, 2.81 mmol) in MeOH (10 mL), $NaBD_4$ (117 mg, 2.80 mmol) was added at room temperature. After stirring for 1 h, the mixture was poured into H_2O, and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=80:20) gave **35** (626 mg, 91%) as an oil. $[\alpha]_D^{17}$=+16.6 (*c* 1.60, $CHCl_3$), IR (film) 3510, 2935, 2855, 1340, 1175 cm^{-1}, The ^1H NMR spectrum indicated that the sample consists of 90:10 diastereomeric isomers, ^1H NMR (C_6D_6) δ 0.01, 0.02 (each 3H, s, Si(C*H*$_3$)$_2$), 0.89 (9H, s, SiC(C*H*$_3$)$_3$), 1.20, 1.22 (each 3H, s, C(C*H*$_3$)$_2$), 2.52, 2.56 (each 3H, s, SO_2CH_3), 3.65 (1H×0.1, br, C1H*H*), 3.79 (1H, dd, *J*=6.4, 11.7 Hz, C6H*H*), 3.82 (1H×0.9, br, C1*H*H), 4.06 (1H, dd, *J*=3.0, 11.7 Hz, C6H*H*), 4.16 (1H, t, *J*=6.8 Hz, C4*H*), 4.31 (1H, t, *J*=6.8 Hz, C3*H*), 4.60 (1H, dd, *J*=3.9, 6.8 Hz, C2*H*), 4.66 (1H, ddd, *J*=3.0, 3.4, 6.8 Hz, C5*H*), ^{13}C NMR (C_6D_6) δ −5.48 (Si(*C*H$_3$)$_2$), 18.5 (Si*C*(CH$_3$)$_3$), 26.0 (SiC(*C*H$_3$)$_3$), 27.0 (C(*C*H$_3$)$_2$), 38.2, 38.4 (SO_2CH_3×2), 61.7 (C1, observed as triplet due to deuterium), 63.5 (*C*6) 76.5 (C4), 77.2 (*C*3), 82.1 (*C*2), 82.5 (C5), 111.5 (*C*(CH$_3$)$_2$), EI-MS (rel. int., %) *m*/*z*=478 (14, $[M-CH_3]^+$), 436 (2.6, $[M-{}^tBu]^+$), 153 (100), EI-HRMS; found: *m*/*z* 478.1332. Calcd for $C_{16}H_{32}DO_{10}S_2Si$: $[M-CH_3]^+$, 478.1346.

4.15. (6*R*)-6-*O*-Benzoyl-6-deuterio-3,4-*O*-isopropylidene-2,5-*O*-bis(methanesulfonyl)-D-mannose (36)

4.15.1. Benzoylation of 35. A mixture of **35** (615 mg, 1.24 mmol), BzCl (210 μL, 1.86 mmol), and pyridine (200 μL, 2.59 mmol) in CH_2Cl_2 (10 mL) was stirred at room temperature for 12 h. The mixture was poured into saturated aqueous $NaHCO_3$ solution and extracted with CH_2Cl_2. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=85:15) gave the corresponding benzoate (674 mg, 90%) as an oil. $[\alpha]_D^{17}$=+28.8 (*c* 0.67, $CHCl_3$), IR (film) 3445, 2930, 2855, 1730, 1360, 1175 cm^{-1}. The ^1H NMR spectrum indicated that the sample consists of 90:10 diastereomeric isomers, ^1H NMR (C_6D_6) δ 0.03, 0.04 (each 3H, s, Si(C*H*$_3$)$_2$), 0.90 (9H, s, SiC(C*H*$_3$)$_3$), 1.21 (6H, s, C(C*H*$_3$)$_2$), 2.46, 2.59 (each 3H, s, SO_2CH_3), 3.81 (1H, dd, *J*=5.4, 11.7 Hz, C6H*H*), 4.08 (1H, dd, *J*=2.9, 11.7 Hz, C6*H*H), 4.55 (1H, dd, *J*=6.4, 7.3 Hz, C4*H*), 4.69 (1H, t, *J*=6.4 Hz, C3*H*), 4.83 (2H, C1*H*, C5*H*), 5.16 (1H, dd, *J*=2.4, 6.4 Hz, C2*H*), 7.08 (3H, aromatic protons), 8.25 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ −5.47, −5.43

(Si(CH_3)$_2$), 18.5 (SiC(CH$_3$)$_3$), 26.0 ((SiC(CH_3)$_3$), 26.95, 27.02 (C(CH_3)$_2$), 38.3, 38.4 (SO_2CH_3×2), 63.1, (*C*6), 63.2 (*C*1, observed as triplet due to deuterium), 76.1 (*C*4) 77.7 (*C*3), 78.5 (*C*2), 81.7 (*C*5), 111.5 (C(CH$_3$)$_2$), 128.6, 130.17, 130.20, 133.2 (aromatic carbons), 166.2 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=582 (17, (M−CH$_3$)$^+$), 540 (24, [M−^{t}Bu]$^+$), 105 (100, PhCO$^+$), EI-HRMS; found: *m*/*z* 582.1606. Calcd for $C_{23}H_{36}DO_{11}S_2Si$: [M−CH$_3$]$^+$, 582.1608.

4.15.2. Desilylation. A mixture of the benzoate obtained in Section 4.15.1 (670 mg, 1.12 mmol), 1.0 M TBAF in THF (1.68 mL, 1.68 mmol), and AcOH (130 μL, 2.24 mmol) in THF (8.0 mL) was stirred at room temperature for 30 min. The mixture was poured into H_2O, and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=75:25) gave the corresponding alcohol (533 mg, 98%) as an oil. $[\alpha]_D^{17}$=+25.8 (*c* 1.56, $CHCl_3$), IR (film) 3535, 2940, 1725, 1345, 1175, 915 cm^{-1}. The ^{1}H NMR spectrum indicated that the sample consists of 90:10 diastereomeric isomers, thus, the signals for the major isomer are described. ^{1}H NMR (C_6D_6) δ 1.14, 1.18 (each 3H, s, C(CH_3)$_2$), 2.40, 2.51 (each 3H, s, SO_2CH_3), 3.67 (1H, dd, *J*=5.4, 12.2 Hz, C1H*H*), 3.85 (1H, dd, *J*=3.4, 12.2 Hz, C1*H*H), 4.38 (1H, dd, *J*=6.4, 6.8 Hz, C3*H*), 4.54 (1H, dd, *J*=5.4, 6.4 Hz, C4*H*), 4.73 (2H, C2*H*, C6*H*), 5.13 (1H, dd, *J*=2.4, 5.4 Hz, C5*H*), 7.06 (3H, aromatic protons), 8.23 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.8, 26.9 (C(CH_3)$_2$), 38.1, 38.4 (SO_2CH_3), 62.1, (*C*1), 63.4 (*C*6, observed as triplet due to deuterium), 76.5 (*C*3) 77.7 (*C*4), 78.6 (*C*5), 81.8 (*C*2), 111.5 (C(CH$_3$)$_2$), 127.8, 128.7, 130.2 133.3 (aromatic carbons), 166.3 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=468 (17, [M−CH$_3$]$^+$), 372 (19, [M−CH$_3$−MsOH]$^+$), 105 (100, PhCO$^+$), EI-HRMS; found: *m*/*z* 468.0704. Calcd for $C_{17}H_{22}DO_{11}S_2$: [M−CH$_3$]$^+$, 468.0744.

4.15.3. Oxidation giving 36. A mixture of the alcohol obtained in Section 4.15.2 (780 g, 1.61 mmol) and Dess-Martin reagent (684 mg, 1.61 mmol) in CH_2Cl_2 (7.0 mL) was stirred at room temperature for 2 h. The mixture was poured into a mixture of saturated aqueous $NaHCO_3$ (50 mL) and 10% $Na_2S_2O_3$ (10 mL) and extracted with ether. The combined extracts were washed with brine, dried over $MgSO_4$, then concentrated in vacuo to give the crude aldehyde **36** (803 mg), ^{1}H NMR ($CDCl_3$) δ 1.32, 1.35 (each 3H, s, C(CH_3)$_2$), 2.90, 3.10 (each 3H, s, OSO_2CH_3), 4.37 (2H, C3*H*, C4*H*), 4.48 (1H, dd, *J*=3.4, 7.3 Hz, C2*H*), 4.70 (1H, d, *J*=2.4 Hz, C6*H*), 4.91 (1H, dd, *J*=2.4, 6.8 Hz, C5*H*), 7.36 (2H, aromatic protons), 7.48 (1H, m, aromatic proton), 7.95 (2H, aromatic protons), 9.68 (1H, s, C1*H*), This sample was subjected to the next step without purification.

4.15.4. (1*R*,6*R*)-6-*O*-Benzoyl-1,6-dideuterio-3,4-*O*-isopropylidene-2,5-*O*-bis(methanesulfonyl)-D-mannitol (37). To a mixture of the crude aldehyde **36** (803 mg) and Ce (III) chloride (1.36 g, 3.65 mmol) in MeOH (10 mL), $NaBD_4$ (153 mg, 3.66 mmol) was added at room temperature. After stirring for 1 h, the mixture was poured into H_2O, and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=70:30) gave **37** (660 mg, 85% in two steps) as an oil. $[\alpha]_D^{17}$=+38.0 (*c* 0.50, $CHCl_3$), IR (film) 3540, 2940, 1725, 1355, 1175, 915 cm^{-1}. The ^{1}H NMR spectrum indicated that the sample consists of 90:10 diastereomeric isomers, thus, the signals for the major product are reported. ^{1}H NMR (C_6D_6) δ 1.16, 1.19 (each 3H, s, C(CH_3)$_2$), 2.45, 2.56 (each 3H, s, OSO_2CH_3), 3.86 (1H, br, C1*H*), 4.41 (1H, dd, *J*=6.4, 6.8 Hz, C3*H*), 4.55 (1H. dd, *J*=5.4, 6.4 Hz, C4*H*), 4.76 (2H, C2*H*, C6*H*), 5.15 (1H, dd, *J*=2.4, 5.4 Hz, C5*H*), 7.08 (3H, aromatic protons), 8.23 (2H, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.8, 26.9 (C(CH_3)$_2$), 38.1, 38.4 (OSO_2CH_3), 62.0, 63.4 (*C*1, *C*6 each signals were observed as triplet because of deuterium attached.), 76.5 (*C*3), 77.7 (*C*4), 78.6 (*C*5), 81.7 (*C*2), 111.5 (C(CH$_3$)$_2$), 130.1, 130.2, 133.3 (aromatic carbons), 166.3 (Ph*C*O), EI-MS (rel. int., %) *m*/*z*=469 (12, [M−CH$_3$]$^+$), 372 (19, [M−CH$_3$−MsOH]$^+$), 105 (100, PhCO$^+$), EI-HRMS; found: *m*/*z* 469.0849. Calcd for $C_{17}H_{21}D_2O_{11}S_2$: [M−CH$_3$]$^+$, 469.0805.

4.15.5. (1*R*,2*S*,3*R*,4*R*,5*S*,6*R*)-1,6-Dideuterio-1,2-5,6-bis-epoxy-3,4-*O*-isopropylidene-3,4-hexandiol (38). A mixture of **37** (146 mg, 302 μmol) and K_2CO_3 (208 mg, 1.51 mmol) in a mixture of MeOH (2.0 mL) and CH_2Cl_2 (2.0 mL) was stirred at 0 °C. The mixture was allowed to warm to room temperature. After 4 h, ether (20 mL) was added and the mixture was stirred for 30 min at room temperature. After filtration under suction, the mixture was poured into H_2O, and extracted with CH_2Cl_2. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=70: 30) gave **38** (37.8 mg, 67%) as an oil. $[\alpha]_D^{17}$=−15.4 (*c* 0.50, $CHCl_3$), IR (film) 1990, 1245, 1215, 1050, 860 cm^{-1}. The ^{1}H NMR spectrum indicated that the sample consists of 90:10 diastereomeric isomers, thus, the signals for the major product are reported. ^{1}H NMR (C_6D_6) δ 1.33, (6H, s, C(CH_3)$_2$), 2.30 (2H, d, *J*=2.9 Hz, C1*H*, C6*H*), 2.54 (2H, dd, *J*=2.9, 3.4 Hz, C2*H*, C5*H*), 3.62 (2H, dd, *J*=2.0, 3.4 Hz, C3*H*, C4*H*), ^{13}C NMR (C_6D_6) δ 26.8 (C(CH_3)$_2$), 42.7 (*C*1 and *C*6, the signal was observed as triplet because of deuterium attached.), 50.8 (*C*2, *C*5) 78.3 (*C*3, *C*4), EI-MS (rel. int., %) *m*/*z*=173 (56, [M−CH$_3$]$^+$), 43 (100), EI-HRMS; found: *m*/*z* 173.0799. Calcd for $C_8H_9D_2O_4$: [M−CH$_3$]$^+$, 173.0781.

4.16. (1*R*,6*R*)-6-*O*-Benzoyl-1,5-dideoxy-1,6-dideuterio-3,4-*O*-isopropylidene-5-thio-D-glucopyranose (39)

4.16.1. Thiepane formation from 38. According to the established procedure by Merrer et al., a mixture of **38** (120 mg, 638 μmol) and $Na_2S{\cdot}9H_2O$ (199 mg, 829 mmol) in DMF (5.0 mL) was stirred at room temperature for 11 h. After concentration in vacuo at 50 °C, the residue was purified by silica gel column chromatography (benzene/EtOAc=60:40) to afford the corresponding thiepane (110 mg, 77%) as an oil. $[\alpha]_D^{17}$=+80.1 (*c* 0.90, MeOH), IR (film) 3480, 1240, 1220 cm^{-1}, ^{1}H NMR (CD_3OD) δ 1.39 (6H, s, C(CH_3)$_2$), 2.62 (2H, d, *J*=5.9 Hz, C2*H*, C7*H*), 3.83 (2H, dt, *J*=2.4, 5.9 Hz, C3*H*, C6*H*), 3.94 (2H, C4*H*, C5*H*), EI-MS (rel. int., %) *m*/*z*=207 (37, [M−CH$_3$]$^+$), 204 (91, [M−H_2O]$^+$), 156 (100), EI-HRMS; found: *m*/*z* 207.0674. Calcd for $C_8H_{11}D_2O_4S$: [M−CH$_3$]$^+$, 207.0658.

4.16.2. Ring contraction by Mitsunobu reaction giving 39. To a mixture of the product obtained in Section 4.16.1 (135 mg, 608 μmol), benzoic acid (96.5 mg, 790 μmol), and PPh_3 (207 mg, 790 μmol) in THF (5.0 mL), diethyl azodicarboxylate (40% toluene solution, 310 μL, 790 μmol) was added and the mixture was stirred at room temperature for 2 h. The mixture was poured into H_2O and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (hexane/EtOAc=75:25) gave **39** (187 mg, 94%) as an oil, $[\alpha]_D^{23}$=+80.1 (*c* 1.42 $CHCl_3$), IR (film) 3450, 2985, 1720, 1270, 1230, 1065, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.31, 1.32 (each 3H, s, C(C*H*$_3$)$_2$), 2.57 (1H, d, *J*=10.3 Hz, C1*H*), 3.17 (1H, t, *J*=8.8 Hz, C3*H*), 3.30 (1H, dd, *J*=4.0, 10.3 Hz, C5*H*), 3.55 (1H, dd, *J*=8.8, 10.3 Hz, C4*H*), 3.92 (1H, dd, *J*=8.8, 10.3 Hz, C2*H*), 4.63 (1 h, d, *J*=4.0 Hz, C6*H*), 7.32 (2H, aromatic protons), 7.45 (1H, m, aromatic proton), 7.94 (2H, aromatic protons), EI-MS (rel. int., %) *m*/*z*=311 (4.0, $[M-CH_3]^+$), 250 (6.0, $[M-H_2O-$acetone$]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m*/*z* 311.0951. Calcd for $C_{15}H_{15}D_2O_5S$: $[M-CH_3]^+$, 311.0920.

4.16.3. (1*R*,6*R*)-2,6-*O*-Dibenzoyl-1,5-dideoxy-1,6-dideuterio-3,4-*O*-isopropylidene-5-thio-D-glucopyranose (*R*)-*S*-oxide (*eq*-41) and its (*S*)-isomer (*ax*-41). Benzoylation of **39** (180 mg, 552 μmol) in a similar manner as described in Section 4.22 gave the corresponding benzoate (170 mg, 72%) as an oil after silica gel column chromatography. $[\alpha]_D^{19}$=+86.3 (*c* 1.05 $CHCl_3$), IR (film) 1720, 1270, 1110, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.24, 1.29 (each 3H, s, C(C*H*$_3$)$_2$), 2.35 (1H, d, *J*=9.8 Hz, C1*H*), 3.13 (1H, dd, *J*=3.9, 10.3 Hz, C5*H*), 3.38 (1H, dd, *J*=8.8, 10.3 Hz, C3*H*), 3.70 (1H, dd, *J*=8.8, 10.3 Hz, C4*H*), 4.82 (1H, d, *J*=3.9 Hz, C6*H*), 5.47 (1H, dd, *J*=9.8, 10.3 Hz, C2*H*), 6.97–7.10 (6H, aromatic protons), 8.08–8.19 (4H, aromatic protons), EI-MS (rel. int., %) *m*/*z*=415 (5.0, $[M-CH_3]^+$), 250 (8.5, $[M-$PhCOOH$-$acetone$]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m*/*z* 415.1145. Calcd for $C_{22}H_{19}D_2O_6S$: $[M-CH_3]^+$, 415.1182.

Oxidation of the product (170 mg, 395 μmol) in the same manner as described in Section 4.3.1 gave *eq*-**41** (75.3 mg, 43%) and *ax*-**41** (54.5 mg, 31%) both as oils after silica gel column chromatography.

4.16.4. Physical data for *eq*-41. $[\alpha]_D^{19}$=+37.8 (*c* 0.65 $CHCl_3$), IR (film) 1725, 1270, 1110, 1040, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.16, 1.24 (each 3H, s, C(C*H*$_3$)$_2$), 2.77 (1H, d, *J*=9.3 Hz, C1*H*), 2.96 (1H, dd, *J*=3.4, 11.2 Hz, C5*H*), 3.34 (1H, dd, *J*=9.3, 11.2 Hz, C4*H*), 4.07 (1H, t, *J*=9.3 Hz, C3*H*), 4.86 (1H, d, *J*=3.4 Hz, C6*H*), 5.37 (1H, t, *J*=9.3 Hz, C2*H*), 6.96–7.18 (6H, aromatic protons), 8.04–8.17 (4H, aromatic protons), EI-MS (rel. int., %) *m*/*z*=447 (0.6, $[M+H]^+$), 431 (1.4, $[M-CH_3]^+$), 266 (1.1, $[M-$PhCOOH$-$acetone$]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m*/*z* 431.1115. Calcd for $C_{22}H_{19}D_2O_7S$: $[M-CH_3]^+$, 431.1132.

4.16.5. Physical data for *ax*-41. $[\alpha]_D^{19}$=+49.6 (*c* 0.52 $CHCl_3$), IR (film) 1720, 1270, 1110, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.17, 1.31 (each 3H, s, C(C*H*$_3$)$_2$), 1.64 (1H, d, *J*=10.3 Hz, C1*H*), 2.70 (1H, dd, *J*=4.4, 9.3 Hz, C5*H*), 3.52 (1H, t, *J*=9.3 Hz, C4*H*), 4.41 (1H, dd, *J*=9.3, 10.3 Hz, C3*H*), 5.15 (1H, d, *J*=4.4 Hz, C6*H*), 6.13 (1H, t, *J*=10.3 Hz, C2*H*), 6.97–7.18 (6H, aromatic protons), 8.05–8.17 (4H, aromatic protons), EI-MS (rel. int., %) *m*/*z*=446 (0.9, M^+), 431 (0.9, $[M-CH_3]^+$), 324 (1.0, $[M-$PhCOOH$]^+$), 266 (5.0, $[M-$PhCOOH$-$acetone$]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m*/*z* 446.1342. Calcd for $C_{23}H_{22}D_2O_7S$: $[M-CH_3]^+$, 446.1366.

4.17. The Pummerer rearrangement of deuterium labelled 41 giving (1*R*,6*R*)-2,6-*O*-dibenzoyl-5-deoxy-1,6-dideutreio-3,4-*O*-isopropylidene-5-thio-D-glucopyranose (42)

4.17.1. Reaction of *eq*-41. Treatment of *eq*-**41** (9.3 mg, 20.8 μmol) in a similar manner as described in Section 4.7.1 gave **42** (5.2 mg, 56%) as an oil after silica gel column chromatography. $[\alpha]_D^{19}$=+74.9 (*c* 0.39 $CHCl_3$), IR (film) 3445, 1720, 1270, 1115, 710 cm^{-1}, ^1H NMR (C_6D_6) δ 1.26, 1.29 (each 3H, s, C(C*H*$_3$)$_2$), 3.63 (1H, dd, *J*=3.9, 10.7 Hz, C5*H*), 3.80 (1H, dd, *J*=8.8, 10.7 Hz, C4*H*), 4.37 (1H, dd, *J*=8.8, 10.8 Hz, C3*H*), 4.77 (1H, d, *J*=3.9 Hz, C6*H*), 5.52 (1H, d, *J*=10.8 Hz, C2*H*), 6.94–7.17 (6H, aromatic protons), 8.17–8.20 (4H, aromatic protons), EI-MS (rel. int., %) *m*/*z*=446 (0.3, M^+), 431 (0.8, $[M-CH_3]^+$), 324 (3.0, $[M-$PhCOOH$]^+$), 266 (1.8, $[M-$PhCOOH$-$acetone$]^+$), 105 (100, $PhCO^+$), EI-HRMS; found: *m*/*z* 446.1380. Calcd for $C_{23}H_{22}D_2O_7S$: $[M-CH_3]^+$, 446.1366.

4.18. Reaction of *ax*-41

Treatment of *ax*-**41** (8.1 mg, 18.1 μmol) in a similar manner as described in Section 4.7.1 gave **42** (7.0 mg, 86%) as an oil after silica gel column chromatography. The ^1H NMR spectrum of the product was identical with that of the authentic sample prepared in Section 4.17.1.

4.18.1. 1,5-Dideoxy-3,4-*O*-isopropylidene-2-*O*-methoxymethyl-5-thio-D-glucopyranose (*S*)-*S*-oxide (43). A mixture of *ax*-**9** (171 mg, 445 μmol) and NaOMe (48.0 mg, 890 μmol) was stirred in MeOH (5.0 mL) at room temperature for 20 h. After addition of ion exchange resin (DOWEX 50W-X4, H^+ form, ca. 100 mg), the mixture was filtered, then concentrated in vacuo. Silica gel column chromatography of the residue (CH_2Cl_2/acetone=75:25) gave **43** (142 mg, 100%) as a solid. Analytical sample was obtained by recrystallization (hexane/EtOAc=50:50) giving needles. Mp=135–136 °C, $[\alpha]_D^{23}$=+11.9 (*c* 2.10, MeOH), IR (KB) 3400, 2985, 2930, 2895, 1155, 1055, 1020 cm^{-1}, ^1H NMR (CD_3OD) δ 1.40, 1.42 (each 3H, s, C(C*H*$_3$)$_2$), 2.69 (1H, dd, *J*=11.3, 14.7 Hz, C1*H*H), 3.04 (1H, dt, *J*=4.4, 11.3 Hz, C5*H*), 3.38 (3H, s, C*H*$_3$O), 3.62 (1H, dd, *J*=4.4, 14.7 Hz C1*H*H), 3.65 (1H, t, *J*=9.3 Hz, C3*H*), 3.88 (1H, t, *J*=10.7 Hz, C4*H*), 3.89 (1H, dd, *J*=8.8, 11.7 Hz, C6*H*H), 4.05 (1H, ddd, *J*=0.9, 4.4, 11.7 Hz, C6*H*H), 4.38 (1H, ddd, *J*=3.9, 9.7, 10.7 Hz, C2*H*), 4.69, 4.83 (each 1H, d, *J*=6.9 Hz, OC*H*HO), ^{13}C NMR (CD_3OD) δ 26.9, 27.0 (C(*C*H$_3$)$_2$), 50.2 (*C*1), 55.9 (*C*H$_3$O), 57.8 (*C*6), 62.9 (*C*5), 72.3 (*C*2), 73.7 (*C*4), 82.7 (*C*3), 97.0 (O*C*H$_2$O), 111.0 (*C*(CH$_3$)$_2$), FD-MS (rel. int., %) *m*/*z*=280 (47, M^+), 265 (97, $[M-Me]^+$), 262 (100, $[M-H_2O]^+$), FD-HRMS; found: *m*/*z* 280.0985. Calcd for $C_{11}H_{20}O_6S$: M^+, 280.0981.

4.18.2. 1,5-Dideoxy-3,4-*O*-isopropylidene-6-*O*-[5′-deoxy-2′,3′,4′,6′-*O*-tetrakis(4-methoxyphenylmethyl)-5′-thio-α-D-glucopyranosyl]-2-*O*-methoxymethyl-5-thio-D-glucopyranose (*S*)-*S*-oxide (45). To a mixture of **43** (30.0 mg, 107 μmol), 2,3,4,6-*O*-tetrakis(4-methoxyphenylmethyl)-5-deoxy-5-thio-α-D-glucopyranosyl trichloroacetimidate (**44**) (80.0 mg, 97.4 μmol), and MS4A (200 mg) in CH_2Cl_2 (5.0 mL), TMSOTf (0.9 μL, 4.9 μmol) in CH_2Cl_2 (100 μL) was added at −78 °C. The mixture was allowed to warm to room temperature for 2 h. After addition of Et_3N (50 μL, 361 mmol), the mixture was filtered through Celite® pad and the filtrate was concentrated in vacuo. Silica gel column chromatography of the residue (benzene/EtOAc=85:15) gave **45** (85.0 mg, 93%) as an oil. $[\alpha]_D^{23}$=+68.7 (*c* 3.8, $CHCl_3$), IR (film) 2995, 2915, 2835, 1510, 1250, 1100, 1035 cm^{-1}, ^1H NMR (C_6D_6) δ 1.21, 1.31 (each 3H, s, C(C*H*$_3$)$_2$), 1.64 (1H, dd, *J*=11.2, 14.7 Hz, C1*H*H), 2.54 (1H, dt, *J*=3.9, 11.7 Hz, C5*H*), 3.08 (3H, s, C*H*$_3$O), 3.13 (1H, dd, *J*=3.9, 14.7 Hz, C1*H*H), 3.26 (1H, t, *J*=9.3 Hz, C3*H*), 3.275, 3.278, 3.296, 3.302 (each 3H, s, C*H*$_3$O×4), 3.75–3.85 (3H, C′5*H*, C6′*H*H, C6*H*H), 3.99 (1H, dd, *J*=2.5, 9.3 Hz, C2′*H*), 4.18–4.24 (3H, C4*H*, C4′*H*, C6′*H*H), 4.28 (1H, d, *J*=11.7 Hz, ArC*H*HO), 4.34 (1H, t, *J*=9.3 Hz, C3′*H*), 4.42–4.47 (3H, ArC*H*$_2$O, OC*H*HO), 4.50 (1H, d, *J*=2.5 Hz, C1′*H*), 4.58 (1H, d, *J*=11.2 Hz, ArC*H*HO), 4.58 (1H, m, C2*H*), 4.65 (1H, t, *J*=10.7 Hz, C6*H*), 4.73–4.74 (2H, OC*H*HO, ArC*H*HO), 5.07 (1H, d, *J*=10.3 Hz, ArC*H*HO), 5.09 (1H, d, *J*=10.8 Hz, ArC*H*HO), 5.21 (1H, d, *J*=10.8 Hz, ArC*H*HO), 6.72–7.41 (16*H*, aromatic protons), ^{13}C NMR (C_6D_6) δ 26.7, 27.0 (C(*C*H$_3$)$_2$), 42.3 (*C*′5), 50.2 (*C*1), 54.66, 54.70, 54.70, 54.72 (*C*H$_3$O×4), 55.2 (*C*H$_3$O), 59.2 (*C*5), 63.3 (*C*6), 68.0 (*C*′6), 71.4 (*C*2), 72.8, 72.9, 75.5, 76.0 (Ar*C*H$_2$O×4), 80.7 (*C*′1), 82.5 (*C*3), 84.1 (*C*′4), 85.3 (*C*′3), 96.1 (*C*′2), 109.7 (O*C*H$_2$O), 113.93, 113.97, 114.0, 114.1, 129.3, 129.6, 129.68, 129.76, 130.8, 131.2, 131.7, 132.2, 159.52, 159.57, 159.67, 159.76 (aromatic carbons), FD-MS (rel. int., %) *m*/*z*=940 (57, $[MH+1]^+$), 939 (100, $[M+H]^+$), 938 (99. M^+), FD-HRMS; found: *m*/*z* 938.3583. Calcd for $C_{49}H_{62}O_{14}S_2$: M^+, 938.3581.

4.19. The Pummerer rearrangement of 45 giving 5-deoxy-3,4-*O*-isopropylidene-6-*O*-[5′-deoxy-2′,3′,4′,6′-*O*-tetrakis(4-methoxyphenylmethyl)-5′-thio-α-D-glucopyranosyl]-2-*O*-methoxymethyl-5-thio-D-glucopyranose (46) and its isomers 47, 48

Treatment of **45** (133 mg, 141 μmol) in a similar manner as described in Section 4.7.1 gave **46** (68.0 mg, 51%), **47** (4,5-olefin, 34.1 mg, 26%), and **48** (5,6-olefin 17.0 mg, 13%) as oils after silica gel column chromatography.

4.19.1. Physical data for 46. IR (film) 3395, 2930, 1510, 1250, 1035 cm^{-1}. The ^1H NMR spectrum of this sample showed that it consists of the two tautomers arising from the C1 anomeric position (isomeric ratio=72:28). Assignments of the signals for the main isomer and some for the minor isomer are described. ^1H NMR (C_6D_6, *a*=0.72, *b*=0.28) δ 1.28 (3H×*b*, s, C*H*$_3$ (minor)), 1.31 (3H×*a*, s, C*H*$_3$ (major)), 1.33 (3H×*b*, s, C*H*$_3$ (minor)), 1.36 (3H×*a*, s, C*H*$_3$ (major)), 2.95 (1H, m, C5*H* or C5′*H*), 3.15 (3H×*a*, s, C*H*$_3$O (major)), 3.20 (3H×*b*, s, C*H*$_3$O (minor)), 3.28 (3H×*b*, s, C*H*$_3$O (minor)), 3.294 (3H×*b*, s, C*H*$_3$O (major)), 3.296 (3H×*b*, s, C*H*$_3$O (minor)), 3.301 (3H×*b*, s, OC*H*$_3$ (minor)), 3.306 (3H×*b*, s, C*H*$_3$O (major)), 3.310 (3H×*b*, s, C*H*$_3$O (major)), 3.318 (3H×*b*, s, C*H*$_3$O (major)), 3.321 (3H×*b*, s, C*H*$_3$O (minor)), 3.43 (1H×*b*, ddd, *J*=2.4, 3.9, 10.2 Hz, C5*H* (minor) or C5′*H* (minor)), 3.47 (1H×*a*, dt, *J*=3.9, 12.0 Hz, C5*H* (major) or C5′*H* (major)), 3.66–4.76 (21H), 4.88–4.94 (2H, m), 4.94 (1H×*b*, br, C1*H* (minor) or C1′*H* (minor)), 4.99 (1H×*b*, d, *J*=10.2 Hz, OCH*H*O (minor) or ArCH*H*O (minor)), 5.02 (1H, × a, d, *J*=10.7 Hz, OCH*H*O (major) or ArCH*H*O (major)), 5.03 (1H, d, *J*=10.7 Hz, OCH*H*O or ArCH*H*O), 6.79 (8H, aromatic protons), 7.15–7.35 (8H, aromatic protons). This sample was used for the next step without further measurement of physical data because of a mixture of anomers.

4.19.2. Physical data for 47 (4,5-olefin). $[\alpha]_D^{22}$=+37.4 (*c* 0.98, $CHCl_3$), IR (film) 2930, 2835, 1510, 1250, 1035 cm^{-1}, ^1H NMR ($CDCl_3$) δ 1.33, 1.37 (each 3H, s, C(C*H*$_3$)$_2$), 2.69 (1H, dd, *J*=8.8, 12.7 Hz, C1*H*H), 2.88 (1H, dd, *J*=5.3, 12.7 Hz, C1*H*H), 3.12 (1H, dt, *J*=3.4, 6.3 Hz, C5′*H*), 3.28 (3H, s, C*H*$_3$O), 3.40 (1H, dd, *J*=3.4, 10.2 Hz, C6′*H*H), 3.59–3.80 (16H, C*H*$_3$O×4, C2′*H*, C4′*H*, C3′*H*, C6′*H*), 3.88 (1H, ddd, *J*=5.3, 8.8, 9.3 Hz, C2*H*), 4.11 (1H, d, *J*=11.7 Hz, C6*H*H), 4.41–4.52 (6H, ArC*H*HO×4, C3*H*, C6*H*H), 4.58 (1H, d, *J*=2.9 Hz, C1′*H*), 4.68–4.80 (7H, ArC*H*HO×5, OC*H*$_2$O), 6.67–7.20 (16H, aromatic protons), ^{13}C NMR ($CDCl_3$) δ 24.9, 26.7 (C(*C*H$_3$)$_2$), 29.1 (*C*1), 41.2 (*C*5′), 55.19, 55.23, 55.25, 55.25 (*C*H$_3$O×4), 55.6 (*C*H$_3$O), 64.3 (*C*6), 67.5 (C6′), 72.4 (Ar*C*H$_2$O), 72.8 (Ar*C*H$_2$O), 75.1 (Ar*C*H$_2$O), 75.7 (Ar*C*H$_2$O), 76.8 (*C*2), 77.5 (*C*3), 78.9 (*C*1′), 81.5 (*C*4′), 83.0 (*C*3′), 83.9 (*C*2′), 95.9 (O*C*H$_2$O), 97.7 (*C*(CH$_3$)$_2$), 112.2 (*C*5), 113.66, 113.70, 113.70, 113.75, 129.39, 129.41, 129.5, 129.7, 130.0, 130.7, 130.8, 131.4 (aromatic carbons), 142.9 (*C*4), 158.97, 159.0, 159.15, 159.20, (aromatic carbons), FD-MS (rel. int., %) *m*/*z*=921 (65, $[MH]^+$), 920 (100, M^+), FD-HRMS; found: *m*/*z* 920.3483. Calcd for $C_{49}H_{60}O_{13}S_2$: M^+, 920.3475.

4.19.3. Physical data for 48 (5,6-olefin). $[\alpha]_D^{22}$=−21.8 (*c* 0.85, $CHCl_3$), IR (film) 2930, 2835, 1610, 1510, 1250, 1035, 515 cm^{-1}, ^1H NMR (C_6D_6) δ 1.34, 1.38 (each 3H, s, C(C*H*$_3$)$_2$), 2.58 (2H, C1*H*$_2$), 3.08 (3H, s, C*H*$_3$O), 3.27 (6H, s, C*H*$_3$O×2), 3.29, 3.31 (each 3H, s, C*H*$_3$O), 3.46 (1H, t, *J*=8.8 Hz, C3*H*), 3.46 (1H, m, C6′*H*H), 3.63 (1H, dt, *J*=3.9, 6.4 Hz, C5′*H*), 3.90 (1H, dd, *J*=2.5, 9.3 Hz, C2′*H*), 3.99 (2H, C6′*H*H, C2*H*), 4.10 (1H, t, *J*=9.3 Hz, C4′*H*), 4.18 (1H, dd, *J*=1.5, 8.8 Hz, C4*H*), 4.20 (1H, d, *J*=11.2 Hz, ArCH*H*O), 4.30 (1H, d, *J*=11.2 Hz, ArCH*H*O), 4.37 (1H, t, *J*=9.3 Hz, C3′*H*), 4.43 (3H, ArC*H*HO×2, OC*H*HO), 4.64 (1H, d, *J*=10.7 Hz, ArC*H*HO), 4.68 (1H, d, *J*=2.5 Hz, C1′*H*), 4.71 (1H, d, *J*=6.8 Hz, OC*H*HO), 4.89 (1H, d, *J*=10.7 Hz, ArC*H*HO), 5.03 (2H, d, *J*=10.7 Hz, ArC*H*HO×2), 6.72–6.85 (8H, aromatic protons), 6.90 (1H, d, *J*=1.5 Hz, C6*H*), 7.15–7.31 (8H, aromatic protons), ^{13}C NMR (C_6D_6, assignment of signals was not performed.) δ 26.9, 27.3, 33.1, 42.6, 54.7, 55.1, 67.6, 72.6, 72.9, 75.5, 75.9, 76.4, 77.4, 82.1, 82.2, 83.7, 83.9, 84.6, 95.7, 109.8, 109.9, 113.9, 114.1, 129.6, 130.5, 131.0 131.6, 132.7, 140.2, 149.4, 158.2, 158.3, 159.7, 159.8, FD-MS (rel. int., %) *m*/*z*=921 (65, $[MH]^+$), 920 (100, M^+), FD-HRMS; found: *m*/*z* 920.3458. Calcd for $C_{49}H_{60}O_{13}S_2$: M^+, 920.3475.

4.20. 5-Deoxy-6-*O*-[5′-deoxy-2′,3′,4′,6′-*O*-tetrakis(4-methoxyphenylmethyl)-5′-thio-α-D-glucopyranosyl]-2-*O*-methoxymethyl-5-thio-α-D-glucopyranose (α-50) and the β-anomer (β-50)

A solution of **46** (61.5 mg, 66.6 μmol) in MeOH (3.0 mL) was stirred with conc. HCl (5.0 μL) at room temperature for 1 h. After neutralization by addition of Et_3N (100 μL), the mixture was concentrated in vacuo. Silica gel column chromatography of the residue (CH_2Cl_2/acetone=90:10) gave α-**50** (36.5 mg, 61%) and β-**50** (18.3 mg, 30%) both as oils.

4.20.1. Physical data for α-50. $[\alpha]_D^{23}$=+123 (*c* 1.20, MeOH), IR (film) 3430, 2930, 1510, 1250, 1100, 1035 cm^{-1}, ^1H NMR (C_6D_6+D_2O) δ 3.24 (3H, s, C*H*$_3$O), 3.30, 3.32, 3.33, 3.34 (each 3H, C*H*$_3$O), 3.57 (1H, ddd, *J*=9.3, 2.9, 3.9 Hz, C5′*H*), 3.66 (1H, dd, *J*=2.0, 9.3 Hz, C6′*H*H), 3.74 (1H, dd, *J*=3.9, 9.3 Hz, C6*H*H), 3.79–3.84 (2H, C2*H*, C5*H*), 3.87–3.93 (2H, C2′*H*, C3*H*), 4.03–4.09 (2H, C4′*H*, C6′*H*), 4.16–4.24 (2H, C3′*H*, C4*H*), 4.28–4.32 (2H, C6*H*H, ArC*H*HO,), 4.40 (1H, d, *J*=11.7 Hz, ArCH*H*O), 4.45 (1H, d, *J*=2.5 Hz, C1′*H*), 4.53, 4.57 (each 1H, d, *J*=11.7 Hz, ArC*H*$_2$O), 4.63–4.66 (2H, OC*H*HO and ArC*H*HO), 4.72 (1H, d, *J*=6.8 Hz, OC*H*HO), 4.87 (1H, d, *J*=2.9 Hz, C1*H*), 4.98 (1H, d, *J*=9.7 Hz, ArC*H*HO), 4.99 (1H, d, *J*=9.8 Hz, ArC*H*HO), 5.13 (1H, d, *J*=10.7 Hz, ArC*H*HO), 6.77–6.85 (8H, aromatic protons), 7.16–7.42 (8H, aromatic protons), FAB-MS (negative mode, rel. int., %) *m*/*z*=897 (1.6, $[M-H]^-$), 537 (4.9, $C_{30}H_{33}O_7S^-$), 148 (100), FAB-HRMS (negative mode); found: *m*/*z* 897.3163. Calcd for $C_{46}H_{57}O_{14}S_2$: $[M-H]^-$, 897.3190.

4.20.2. Physical data for β-50. $[\alpha]_D^{23}$=+93.9 (*c* 1.40, MeOH), IR (film) 3450, 2910, 1610, 1510, 1250, 1100, 1035 cm^{-1}, ^1H NMR (C_6D_6) δ 2.97 (1H, m, C5*H*), 3.00 (3H, s, C*H*$_3$O), 3.29 (6H, s, C*H*$_3$O×2), 3.30, 3.31 (each 3H, s, C*H*$_3$O), 3.31 (1H, m, C6*H*H), 3.48 (1H, t, *J*=8.3 Hz, C3*H*), 3.53 (1H, ddd, *J*=2.9, 4.9, 10.7 Hz, C5′*H*), 3.60 (1H, dd, *J*=2.4, 9.7 Hz, C6′*H*H), 3.69 (1H, dd, *J*=6.8, 7.8 Hz, C2*H*), 3.88 (1H, dd, *J*=6.9, 9.3 Hz, C2′*H*), 3.93–4.00 (2H, C4H, C6′*H*H), 4.03 (1H, dd, *J*=9.3, 10.7 Hz, C4′*H*), 4.19 (1H, t, *J*=9.3 Hz, C3′*H*), 4.25–4.29 (2H, ArC*H*HO, C6*H*H), 4.34 (1H, d, *J*=10.7 Hz, ArC*H*HO), 4.35 (1H, d, *J*=3.4 Hz, C1′*H*), 4.45–4.55 (3H, OC*H*$_2$O, ArC*H*HO), 4.64 (1H, d, *J*=10.7, ArC*H*HO), 4.67 (1H, d, *J*=6.9 Hz, C1*H*), 4.93 (1H, d, *J*=10.8 Hz, ArC*H*HO), 5.02 (1H, d, *J*=10.8 Hz, ArC*H*HO), 5.06 (1H, d, *J*=10.8 Hz, ArC*H*HO), 6.75–6.83 (8H, aromatic protons), 7.18, 7.21, 7.29, 7.35 (each br d, *J*=8.8 Hz, aromatic protons), FAB-MS (negative mode, rel. int., %) *m*/*z*=897 (2.1, $[M-H]^-$), 537 (8.7, $C_{30}H_{33}O_7S^-$), 148 (100), FAB-HRMS (negative mode); found: *m*/*z* 897.3218. Calcd for $C_{46}H_{57}O_{14}S_2$: $[M-H]^-$, 897.3190.

4.20.3. 1,3,4-*O*-Triacetoxy-5-deoxy-6-*O*-[5′-deoxy-2′,3′,4′,6′-*O*-tetrakis(4-methoxyphenylmethyl)-5′-thio-α-D-glucopyranosyl]-2-*O*-methoxymethyl-5-thio-α-D-glucopyranose (α-51). A mixture of α-**50** (30.0 mg, 33.4 μmol), Ac_2O (100 μL, 1.06 mmol), and pyridine (200 μL, 2.48 mmol) in CH_2Cl_2 (500 μL) was stirred at room temperature for 33 h. After concentration in vacuo, silica gel column chromatography of the residue (benzene/EtOAc=85:15) gave α-**51** (28 mg, 83%) in an almost pure form as an oil. $[\alpha]_D^{23}$=+170 (*c* 0.15, $CHCl_3$), IR (film) 2955, 2840, 1750, 1510, 1245, 1215, 1100, 1035 cm^{-1}. The ^1H NMR spectrum of this sample showed that it contains small amount of β-**51** (α-**51**/β-**51**=97:3). Assignments of the signals for the main isomer and some for the minor isomer are described. ^1H NMR (C_6D_6, *a*=0.97, *b*=0.03) δ 1.50 (3H×*a*, s, C*H*$_3$CO (major)), 1.54 (3H×*b*, s, C*H*$_3$CO (minor)), 1.73, (3H, s, C*H*$_3$CO), 1.80 (3H×*b*, s, C*H*$_3$CO (minor)), 1.86 (3H×*a*, s, C*H*$_3$CO (minor)), 3.06 (3H×*a*, s, C*H*$_3$O (major)), 3.07 (3H×*b*, s, C*H*$_3$O (major)), 3.22 (1H×*b*, C6*H*H (minor)), 3.27 (1H, m, C6*H*H), 3.28, 3.29, 3.30, 3.30 (each 3H, s, C*H*$_3$O), 3.54 (1H, ddd, *J*=2.9, 4.4,, 10.8 Hz, C5′*H*), 3.60 (1H, dt, *J*=10.7, 3.9 Hz, C5*H*), 3.66 (1H, dd, *J*=2.4, 9.7 Hz, C6′*H*H), 3.87 (2H, C2*H*, C2′*H*), 4.07 (3H, C4′*H*, C6H*H*, C6′H*H*), 4.21 (1H, t, *J*=9.3 Hz, C3′*H*), 4.26 (1H, d, *J*=2.9 Hz, C1′*H*), 4.32 (3H, OC*H*$_2$O, ArC*H*HO), 4.39 (1H, d, *J*=6.9 Hz, ArC*H*HO), 4.46, 4.53 (each 1H, d, *J*=11.3 Hz, OC*H*HO), 4.68 (1H, d, *J*=10.7 Hz, ArC*H*HO), 4.87 (1H, d, *J*=10.3 Hz, ArC*H*HO), 5.02 (1H, d, *J*=10.7 Hz, ArC*H*HO), 5.06 (1H, d, *J*=10.3 Hz, ArC*H*HO), 5.23 (1H × b, dd, *J*=8.3, 10.3 Hz, C3*H* (minor)), 5.61 (1H, t, *J*=9.8 Hz, C4*H*), 5.72 (1H×*a*, t, *J*=9.8 Hz, C3*H* (major)), 6.05 (1H×*b*, d, *J*=8.3 Hz, C1*H* (minor)), 6.23 (1H×*a*, d, *J*=2.9 Hz, C1*H* (major)), 6.74–6.84 (8H, aromatic protons), 7.21 (4H, aromatic protons), 7.32 (4H, aromatic protons), FD-MS (rel. int., %) *m*/*z*=1025 (17, $[M+H]^+$), 1024 (7.6, M^+), 1023 (11, $[M-H]^+$), 903 (100, $[M-(CH_3OPhCH_2)+H]^+$), FD-HRMS; found: *m*/*z* 1024.3593. Calcd for $C_{52}H_{64}O_{17}S_2$: M^+, 1024.3585.

4.20.4. 1,3,4-*O*-Triacetoxy-5-deoxy-6-*O*-[5′-deoxy-2′,3′,4′,6′-*O*-tetrakis(4-methoxyphenylmethyl)-5′-thio-α-D-glucopyranosyl]-2-*O*-methoxymethyl-5-thio-β-D-glucopyranose (β-51). Treatment of β-**50** (9.0 mg, 10 μmol) in a similar manner as described in Section 4.20.3 gave β-**51** (9.0 mg, 89%) as an oil after silica gel column chromatography. $[\alpha]_D^{23}$=+65.3 (*c* 0.10, $CHCl_3$), IR (film) 2925, 2860, 1750, 1510, 1245, 1215, 1100, 1035 cm^{-1}. The ^1H NMR spectrum of this sample showed that it contains small amount of α-**51** (α-**51**/β-**51**=9:91). Assignments of the signals for the main isomer and some for the minor isomer are described. ^1H NMR (C_6D_6, *a*=0.09, *b*=0.91) δ 1.50 (3H×*b*, s, C*H*$_3$CO (minor)), 1.54 (3H×*a*, s, C*H*$_3$CO (major)), 1.73 (3H×*b*, s, C*H*$_3$CO (minor)), 1.74 (3H×*a*, s, C*H*$_3$CO (major)), 1.80 (3H×*a*, s, C*H*$_3$CO (major)), 1.86 (3H×*b*, s, C*H*$_3$CO (minor)), 2.72 (1H, dt, *J*=3.9 Hz, C5′*H*), 3.07 (3H, s, C*H*$_3$O), 3.22 (1H, dd, *J*=3.9, 9.8 Hz, C6*H*H), 3.28, 3.29, 3.30, 3.30 (each 3H, s, C*H*$_3$O), 3.55 (1H, ddd, *J*=2.4, 3.9, 10.7 Hz, C5′*H*), 3.66 (1H, dd, *J*=2.4, 9.7 Hz, C6′*H*H), 3.88 (1H, dd, *J*=3.0, 8.8 Hz, C2′*H*), 3.89 (1H, t, *J*=8.3 Hz, C2*H*), 3.94 (1H, dd, *J*=3.9, 9.8 Hz, C6*H*H), 4.08 (2H, C4*H*, C6′*H*H), 4.21 (1H, t, *J*=8.8 Hz, C3′*H*), 4.25 (1H, d, *J*=3.0 Hz, C1′*H*), 4.30 (1H, d, *J*=11.7 Hz, ArC*H*HO), 4.35 (1H, d, *J*=11.7 Hz, ArC*H*HO), 4.46 (2H, s, OC*H*$_2$O), 4.47 (1H, d, *J*=11.2 Hz, ArC*H*HO), 4.56 (1H, d, *J*=11.2 Hz, ArC*H*HO), 4.69 (1H, d, *J*=10.7 Hz, ArC*H*HO), 4.90 (1H, d, *J*=10.3 Hz, ArC*H*HO), 5.04 (1H, d, *J*=10.3 Hz, ArC*H*HO), 5.05 (1H, d, *J*=10.7 Hz, ArC*H*HO), 5.23 (1H×*a*, dd, *J*=8.3, 10.3 Hz, C3*H* (major)), 5.56 (1H×*a*, dd, 8.3, 10.3 Hz, C4*H* (major)), 5.61 (1H×*b*, t, *J*=9.8 Hz, C4*H* (minor)), 5.72 (1H×*b*, t, *J*=9.8 Hz, C3*H* (minor)), 6.05 (1H, d, *J*=8.3 Hz, C1*H*), 6.23 (1H×*b*, d, *J*=2.9 Hz, C1*H* (minor)), 6.74–6.83 (8H, aromatic protons), 7.20 (4H,

aromatic protons), 7.32 (4H, m, aromatic protons), FD-MS (rel. int., %) *m/z*=1024 (24, M^+), 1023 (24, $[M-H]^+$), 903 (100, $[M-(CH_3OPhCH_2)+H]^+$), FD-HRMS; found: *m/z* 1024.3566. Calcd for $C_{52}H_{64}O_{17}S_2$: M^+, 1024.3585.

4.21. 3,4-*O*-Diacetoxy-5-deoxy-6-*O*-[5′-deoxy-2′,3′,4′,6′-*O*-tetrakis(4-methoxyphenylmethyl)-5′-thio-α-D-glucopyranosyl]-2-*O*-methoxymethyl-5-thio-α-D-glucopyranose (α-52) and the β-anomer (β-52)

A mixture of α-**51** (25.1 mg, 24.9 μmol) and hydrazine acetate (2.8 mg, 29.0 μmol) in DMF (1.0 mL) was stirred at room temperature for 12 h. The mixture was poured into H_2O and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (benzene/EtOAc=80:20) gave α-**52** (19.4 mg, 79%) and β-**52** (1.9 mg, 7.8%) both as oils.

4.21.1. Physical data for α-52. The ^{1}H NMR spectrum suggested that the deuterium atom was completely retained through the reaction.

4.21.2. Physical data for β-52. The ^{1}H NMR spectrum suggested that the deuterium atom was completely retained through the reaction.

4.21.3. Physical data for α-55. $[\alpha]_D^{23}$=+113 (*c* 1.35, $CHCl_3$), IR (film) 2930, 1730, 1510, 1245, 1100, 1030 cm^{-1}, ^{1}H NMR ($CDCl_3$) δ 1.84, 1.89 (each 3H, s, C*H*$_3$CO), 3.04 (1H, ddd, *J*=2.5, 3.9, 10.7 Hz, C5″*H*), 3.16 (3H, s, C*H*$_3$O), 3.20 (1H, dd, *J*=2.9, 10.2 Hz, C6′*H*H), 3.35 (1H, dd, *J*=2.5, 9.8 Hz, C6″*H*H), 3.41 (3H, s, C*H*$_3$O), 3.44 (2H, C5′*H*, C6*H*H), 3.60–3.74 (3H, C2″*H*, C3″*H*, C4″*H*), 3.63, 3.66, 3.67, 3.69 (each 3H, s, C*H*$_3$O), 3.80 (1H, dd, *J*=3.9, 9.8 Hz, C6″*H*H), 3.86 (1H, dd, *J*=2.4, 9.7 Hz, C2′*H*), 3.89 (1H, dd, *J*=4.4, 10.2 Hz, C6′*H*H), 4.05 (1H, dd, *J*=7.3, 10.2 Hz, C6*H*H), 4.25–4.35 (4H, C1″*H*, C5*H*, ArC*H*$_2$O), 4.36 (1H, d, *J*=10.7 Hz, ArC*H*HO), 4.47, 4.51 (each 1H, d, *J*=11.7 Hz, ArC*H*HO), 4.52 (2H, s, OC*H*$_2$O), 4,60 (1H, d, *J*=10.2 Hz, ArC*H*HO), 4.61 (1H, d, *J*=2.4 Hz, C1′*H*), 4,68 (1H, d, *J*=10.7 Hz, ArC*H*HO), 4,73 (1H, d, *J*=10.2 Hz, ArC*H*HO), 5.11–5.20 (3H, C1*H*, C2*H*, C4′*H*), 5.34 (1H, t, *J*=9.7 Hz, C3′*H*), 5.39 (1H, t, *J*=10.2 Hz, C4*H*), 6.05 (1H, t, *J*=10.2 Hz, C3*H*), 6.68–6.78 (8H, aromatic protons), 6.98–7.40 (17H, aromatic protons), 7.74–7.87 (6H, aromatic protons), FD-MS (rel. int., %) *m/z*=1470 (12, M^+), 1469 (18, $[M-H]^+$), 1350 (92, $[M-(CH_3OPhCH_2+H)]^+$), 1349 (100, $[M-PhCOO]^+$), FD-HRMS; found: *m/z* 1470.4965. Calcd for $C_{78}H_{86}O_{24}S_2$: M^+, 1470.4951.

4.21.4. Physical data for β-55. $[\alpha]_D^{27}$=+75.1 (*c* 0.77, $CHCl_3$), IR (film) 2930, 1730, 1510, 1245, 1095, 1030 cm^{-1}, ^{1}H NMR ($CDCl_3$) δ 1.86, 1.94 (each 3H, s, C*H*$_3$CO), 3.02 (2H, C5′*H*, C5″*H*), 3.21 (3H, s, C*H*$_3$O), 3.27 (1H, dd, *J*=3.9, 9.8 Hz, C6′*H*H), 3.31 (3H, s, C*H*$_3$O), 3.33 (1H, dd, *J*=2.0, 9.8 Hz, C6″*H*H), 3.57–3.73 (5H, C2″*H*, C3″*H*, C4″*H*, C6*H*, C6′*H*), 3.64, 3.65, 3.67, 3.68 (each 3H, s, C*H*$_3$O), 3.79 (2H, C2′*H*, C6″*H*H), 3.88 (1H, dd, *J*=2.4, 11.2 Hz, C6*H*H), 4.08 (1H, ddd, *J*=2.4, 5.8, 9.8 Hz, C5*H*), 4.14 (1H, d, *J*=2.9 Hz, C1″*H*), 4.27, 4.31 (each 1H, d, *J*=12.2 Hz, ArC*H*HO), 4.32 (1H, d, *J*=10.3 Hz, ArC*H*HO), 4.41 (1H, d, *J*=11.8 Hz, ArC*H*HO), 4.47 (1H, d, *J*=7.8 Hz, C1′*H*), 4.53 (1H, d, *J*=11.8 Hz, ArC*H*HO), 4,57 (1H, d, *J*=10.3 Hz, ArC*H*HO), 4.61 (1H, d, *J*=6.9 Hz, OC*H*HO), 4.66 (1H, d, *J*=10.3 Hz, ArC*H*HO), 4,69 (1H, d, *J*=10.3 Hz, ArC*H*HO), 4.74 (1H, d, *J*=6.9 Hz, OC*H*HO), 4.88 (1H, dd, *J*=8.3, 9.3 Hz, C3′*H*), 5.10 (3H, C1*H*, C2*H*, C4′*H*), 5.36 (1H, t, *J*=9.8 Hz, C4*H*), 6.00 (1H, t, *J*=9.8 Hz, C3*H*), 6.67–6.73 (9H, aromatic protons), 6.94–7.40 (14H, aromatic protons), 7.71–7.86 (6H, aromatic protons), FD-MS (rel. int., %) *m/z*=1471 (26, $[M+H]^+$), 1470 (19, M^+), 1469 (24, $[M-H]^+$), 1350 (100, $[M-(CH_3OPhCH_2)+H]^+$), FD-HRMS; found: *m/z* 1470.4956. Calcd for $C_{78}H_{86}O_{24}S_2$: $[M]^+$, 1470.4951.

4.22. Methyl 6-*O*-[5′-deoxy-6′-*O*-(5″-deoxy-5″-thio-α-D-glucopyranosyl)-5′-thio-α-D-glucopyranosyl]-α-D-glucopyranoside (α-58)

4.22.1. Removal of the MPM ethers giving methyl 6-*O*-[3′,4′-*O*-diacetyl-5′-deoxy-6′-*O*-[5″-deoxy-4″,6″-*O*-(4-methoxyphenylmethylidene)-5″-thio-α-D-glucopyranosyl]-2′-*O*-methoxymethyl-5′-thio-α-D-glucopyranosyl]-2,3,4-*O*-tribenzoyl-α-D-glucopyranoside (α-56). A mixture of α-**55** (65.1 mg, 44.2 μmol) and DDQ (50 mg, 220 μmol) in a mixture of CH_2Cl_2 (1.0 mL) and H_2O (100 μL) was stirred at room temperature for 1 h. The mixture was poured into saturated aqueous $NaHCO_3$ and extracted with EtOAc. The combined extracts were washed with brine, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (benzene/EtOAc=70:30) gave α-**56** (34.0 mg, 70%) as an oil. $[\alpha]_D^{23}$=+176 (*c* 3.54, $CHCl_3$), IR (film) 1455, 2930, 1730, 1280, 1250, 1105, 1070, 1025 cm^{-1}, ^{1}H NMR ($C_6D_6+D_2O$) δ 1.80, 1.81 (each 3H, s, C*H*$_3$CO), 3.09, 3.29, 3.35 (each 3H, s, C*H*$_3$O), 3.45 (1H, dd, *J*=2.4, 10.2 Hz, C6′*H*H), 3.54 (2H, C6*H*H, C6″*H*H), 3.65 (1H, dt, *J*=3.9, 9.7 Hz, C″5*H*), 3.75 (1H, ddd, *J*=3.5, 4.9, 11.3 Hz, C5′*H*), 3.83 (1H, t, *J*=9.7 Hz, C4″*H*), 3.93 (1H, dd, *J*=2.4, 9.8 Hz, C2′*H*), 4.02 (2H, C6′*H*H, C2″*H*), 4.23 (3H, C6*H*H, C3″*H*, C6″*H*H), 4.43 (1H, d, *J*=2.9 Hz, C1″*H*), 4.43 (1H, m, C5*H*), 4.46 (2H, s, OC*H*$_2$O), 4.51 (1H, d, *J*=2.5 Hz, C1′*H*), 5.36 (1H, d, *J*=3.5 Hz, C1*H*), 5.49 (1H, s, ArC*H*(OR)$_2$), 5.58 (2H, C2H, C4′*H*), 5.86 (2H, C3′*H*, C4*H*), 6.65 (1H, t, *J*=9.8 Hz, C3*H*), 6.81–7.04 (11H, aromatic protons), 7.61–8.14 (8H, aromatic protons), FD-MS (rel. int., %) *m/z*=1109, (69, $[M+H]^+$), 1008 (100, M^+), FD-HRMS; found: *m/z* 1108.3058. Calcd for $C_{54}H_{66}O_{21}S_2$: M^+, 1108.3069.

4.22.2. Removal of the acetyl and benzoyl groups giving methyl 6-*O*-[5′-deoxy-6′-*O*-[5″-deoxy-4″,6″-*O*-(4-methoxyphenylmethylidene)-5″-thio-α-D-glucopyranosyl]-2′-*O*-methoxymethyl-5′-thio-α-D-glucopyranosyl]-α-D-glucopyranoside. A mixture of the benzoate obtained in Section 4.23.1. (33.0 mg, 29.8 μmol) and NaOMe (9.6 mg, 178 μmol) in MeOH (1.0 mL) was stirred at room temperature for 2.5 h. To the mixture DOWEX 50W-X4 (H^+ form, 10 mg) was added. After stirring for another 5 min, the mixture was filtrated and concentrated in vacuo. Silica gel column chromatography of the residue (EtOAc/MeOH=80:20) gave the corresponding alcohol (16.7 mg, 79%) as an oil. $[\alpha]_D^{25}$=+258 (*c* 1.5, MeOH), ^{1}H NMR (CD_3OD) δ 3.34 (3H, s, C*H*$_3$O), 3.35–3.45 (4H), 3.39, 3.42 (each 3H, s, C*H*$_3$O), 3.55–3.87 (13H), 4.01 (1H,

dd, *J*=7.8, 10.3 Hz, C6′*H*H or C6″*H*H), 4.11 (1H, dd, *J*=5.9, 10.7 Hz, C6*H*H), 4.14 (1H, dd, *J*=4.4, 10.7 Hz, C6′*H*H or C6″*H*H), 4.67 (1H, d, *J*=3.9 Hz, C1″*H*), 4.71 (1H, d, *J*=2.9 Hz, C1′*H*), 4.78 (2H, s, OCH_2O), 4.81 (1H, br, C1*H*), 5.60 (1H, s, ArC*H*$(OR)_2$), 6.90, 7.42 (each 2H, br, *J*=8.3 Hz, aromatic protons), FAB-MS (negative mode, rel. int., %) *m*/*z*=747 (23, $[M+Cl]^-$), 711 (30, $[M-H]^-$), 255 (100), 148 (99), FAB-HRMS (negative mode); found: *m*/*z* 711.1994. Calcd for $C_{29}H_{43}O_{16}S_2$: $[M-H]^-$, 711.1993.

4.22.3. Removal of the MOM and methoxybenzylidene groups under acidic conditions giving α-58. A solution of the MOM ether obtained in Section 4.22.2 (15.0 mg, 21.0 mmol) in MeOH (500 μL) was stirred with conc. HCl (5.0 μL) at room temperature for 1 day. To the mixture DIAION DA30 (free base form, 10 mg) was added. After stirring for another 5 min, the mixture was filtered and concentrated in vacuo. The residue was passed through SepPack (ODS, MeOH/H_2O=10:90) and the eluates were concentrated. Medium pressured column chromatography (ODS, MeOH/H_2O=10:90) of the residue gave α-**58** (9.0 mg, 78%) as an oil. $[\alpha]_D^{23}$=+292 (*c* 0.73, H_2O), IR spectrum was not measured because this sample was soluble only in H_2O. ^{1}H NMR (D_2O) δ 3.08 (1H, ddd, *J*=2.9, 5.4, 9.3 Hz, C5′*H* or C5″*H*), 3.19 (1H, ddd, *J*=3.0, 7.9, 10.3 Hz, C5′*H* or C5″*H*), 3.34 (3H, s, CH_3O), 3.41 (1H, t, *J*=9.2 Hz, C4*H*), 3.48 (1H, dd, *J*=3.9, 9.8 Hz, C2*H*), 3.51–3.62 (6H, m), 3.73–3.86 (6H, m), 3.98 (1H, dd, *J*=7.9, 10.3 Hz, C6′*H*H or C6″*H*H), 4.09 (1H, dd, *J*=4.4, 11.2 Hz, C6*H*H), 4.65 (1H, d, *J*=3.4 Hz, C1′*H* or C1″*H*), 4.66 (1H, d, *J*=3.9 Hz, C1′*H* or C1″*H*), 4.73 (1H, d, *J*=3.9 Hz, C1*H*), FAB-MS (negative mode, rel. int., %) *m*/*z*=549 (13, $[M-H]^-$), 195 (27, $[C_6H_{11}O_5S]^-$), 148 (100), FAB-HRMS (negative mode); found: *m*/*z* 549.1306. Calcd for $C_{19}H_{33}O_{14}S_2$: $[M-H]^-$, 549.1312.

4.23. Methyl 6-*O*-[5′-deoxy-6′-*O*-(5″-deoxy-5″-thio-α-D-glucopyranosyl)-5′-thio-β-D-glucopyranosyl]-α-D-glucopyranoside (β-58)

4.23.1. Removal of the MPM ethers giving methyl 6-*O*-[3′,4′-*O*-diacetyl-5′-deoxy-6′-*O*-[5″-deoxy-5″-thio-α-D-glucopyranosyl]-2′-*O*-methoxymethyl-5′-thio-β-D-glucopyranosyl]-2,3,4-*O*-tribenzoyl-α-D-glucopyranoside (57) and its 4″,6″-*O*-(4-methoxybenzylidene)acetal (β-56). Treatment of β-**55** (40.3 mg, 27.4 μmol) with DDQ (31 mg, 137 μmol) in a similar manner as described in Section 4.22.1 gave benzylidene acetal β-**56** (13.3 mg, 44%) and **57** (7.0 mg, 26%) as oils after silica gel column chromatography. The methoxybenzylidene group at C4″, C6″ position was cleaved during measurement of its ^{1}H NMR spectrum in $CDCl_3$ (a signal appeared at 9.77 ppm corresponding to the decomposed anisaldehyde and the intensity of this signal gradually increased). Thus, the sample (13.3 mg) was purified again by silica gel column chromatography to give **57** (12.1 mg, 45% two steps). Thus, the total yield of the tetraol **57** was 71%. $[\alpha]_D^{23}$=+114 (*c* 1.41, $CHCl_3$), IR (film) 3450, 1730, 1280, 1250, 1095, 1025 cm^{-1}, ^{1}H NMR ($CDCl_3$) δ 1.95, 1.96 (each 3H, s, CH_3CO), 3.03 (2H, C5′*H*, C5″H), 3.22 (3H, s, CH_3O), 3.36 (1H, m, C6′*H*H), 3.37 (3H, s, CH_3O), 3.53–3.70 (5H, m), 3.77 (1H, dd, *J*=5.7, 11.7 Hz, C6″*H*H), 3.84 (2H, C2′*H*, C6*H*H), 3.95 (1H, dd, *J*=4.8, 10.2 Hz, C6′*H*H), 4.12 (1H, ddd, *J*=2.4, 5.9, 9.7 Hz, C5*H*), 4.44 (1H, d, *J*=2.5 Hz, C1″*H*), 4.56 (1H, d, *J*=7.3 Hz, C1′*H*), 4.61, 4.75 (each 1H, d, *J*=6.9 Hz, OC*H*HO), 4.91 (1H, dd, *J*=8.3, 9.3 Hz, C3′*H*), 5.12 (2H, C1*H*, C2*H*), 5.22 (1H, t, *J*=9.8 Hz, C4′*H*), 5.39 (1H, t. *J*=9.7 Hz, C4*H*), 6.02 (1H, t, *J*=9.7 Hz, C3*H*), 7.16–7.43 (9H, aromatic protons), 7.71–7.86 (6H, aromatic protons).

4.23.2. Removal of the acetyl and the benzoyl groups. Treatment of the tetraol **57** (16.8 mg, 16.9 μmol) in a similar manner as described in Section 4.22.2 gave the corresponding nonanol (10.1 mg, 100%) as an oil. $[\alpha]_D^{25}$=+29.8 (*c* 0.75, MeOH), ^{1}H NMR (CD_3OD) δ 3.00 (1H, ddd, *J*=3.9, 7.8, 11.7 Hz, C5′*H* or C5″*H*), 3.12 (1H, ddd, *J*=3.0, 7.9, 12.7 Hz, C5′*H* or C5″*H*), 3.23–3.41 (3H), 3.34, 3.40 (each 3H, s, CH_3O), 3.49–3.73 (8H), 3.79–3.85 (3H), 4.00 (1H, dd, *J*=7.8, 9.8 Hz, C6′*H*H or C6″*H*H), 4.05 (1H, dd, *J*=1.5, 10.7 Hz, C6*H*H), 4.58 (1H, d, *J*=3.0 Hz, C1″*H*), 4.61 (1H, d, *J*=8.3 Hz, C1′*H*), 4.63 (1H, d, *J*=4.4 Hz, C1*H*), 4.81, 4.94 (each 1H, d, *J*=6.3 Hz, OC*H*HO), FD-MS (rel. int., %) *m*/*z*=617 (100, $[M+Na]^+$), FD-HRMS; found: *m*/*z* 617.1536. Calcd for $C_{21}H_{38}O_{15}S_2Na$: $[M+Na]^+$, 617.1550.

4.23.3. Removal of the MOM group under acidic conditions giving β-58. Treatment of the nonanol obtained in Section 4.23.2. (7.0 mg, 11.8 μmol) in a similar manner as described in Section 4.22.3 followed by also a similar purification gave the β-**58** (2.6 mg, 40%) as an oil. $[\alpha]_D^{23}$=−75.0 (*c* 0.20, H_2O), IR spectrum was not measured because this sample was soluble only in H_2O. ^{1}H NMR (D_2O) δ 3.19–3.25 (2H, m, C5′*H*, C5″*H*), 3.39 (1H, t, *J*=9.3 Hz, C3′*H* or C3″*H*), 3.49 (3H, s, CH_3O), 3.54 (1H, t, *J*=9.8 Hz, C4*H*), 3.61 (1H, dd, *J*=3.4, 9.8 Hz, C2*H*), 3.64–3.76 (6H, m), 3.82 (1H, m, C5*H*), 3.89–4.01 (4H, m), 4.07–4.15 (2H, [C6*H*H, C6′*H*H] or [C6*H*H, C6″*H*H]), 4.70 (1H, d, *J*=9.3 Hz, C1′*H*), 4.80 (1H, d, *J*=2.4 Hz, C1″*H*), 4.84 (1H, d, *J*=3.4 Hz, C1*H*), FAB-MS (negative mode, rel. int., %) *m*/*z*=549 (11, $[M-H]^-$), 195 (50, $[C_6H_{11}O_5S]^-$), 148 (100), FAB-HRMS (negative mode); found: *m*/*z* 549.1318. Calcd for $C_{19}H_{33}O_{14}S_2$: $[M-H]^-$, 549.1312.

5. Supporting information

^{1}H NMR spectra are given for new compounds.

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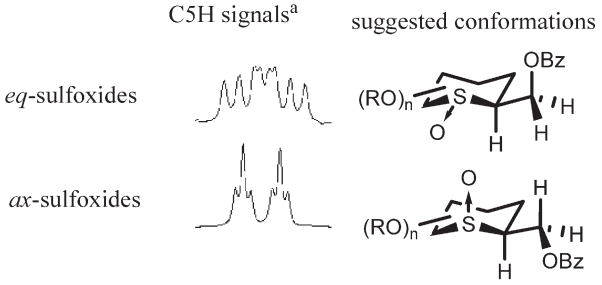
24. Interestingly, the configuration of the sulfoxide influences the conformation around its C5–C6 bonds. The signal patterns of the C5H in ^{1}H NMR spectrum clearly divided into two groups, the *ax*- and *eq*-sulfoxide groups. The coupling constants between C5H and both of the C6 methylene protons in the equatorial sulfoxides *eq*-**9**–**12** were 2.5–5.4 Hz, which suggests that the relationship between H5 and H6 and H6′ of the equatorial isomers were both *gauche*, that is the conformation about the C5–C6 bond is *gg*. In contrast, the sizes of the coupling constants between H5 and one of the two H6s for the corresponding axial sulfoxides of **9**–**12** were large (9.3–11.7 Hz), indicating that these protons had an *anti* relationship. It appears that the potential 1,3-diaxial relationship with the equatorial oxygen atom O-4 causes the *tg* conformation be of high energy and similarly the potential 1,3-diaxial relationship with the axial sulfoxide oxygen atom causes the *gg* conformation be of high energy. Thus, the axial sulfoxides of **9**–**12** adopt the *tg* conformations about the C5–C6 bond almost exclusively, as shown.



(a) The figure shows the C5H proton signals observed in ***eq-11*** *and* ***ax-11****.*

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37. Very small differences were observed in the chemical shifts for the C1H*ax* (Δδ 0.012 ppm), the remained C6H (Δδ 0.018 ppm), and C2H (Δδ 0.009 ppm) due to the isotope effect as shown in Figure 3 of the text.
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