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Synthesis of a trigalacturonic acid analogue mimicking the expected transition state in the glycosidases

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ABSTRACT

A trigalacturonic acid analogue carrying a cyclohexene framework in place of the central pyranose ring was synthesized as a molecular probe for the mechanistic investigation of *endo*-polygalacturonase 1 (*endo*-PG 1). Preliminary enzymatic studies revealed that this analogue inhibited *endo*-PG 1 activity by about 30% at 0.3 mM concentration.

1. Introduction

Oligomers of pectins known as oligopectins have received special attention lately as substances not only governing plant growth[1,2] but serving as functional foods[3,4] as well. In the course of our investigations on the detailed mechanism of *endo*-glycosidases, we focused on *endo*-polygalacturonase 1 (*endo*-PG 1), isolated from *Stereum purpureum* by one of the present authors, Miyairi,[5] which led to a nice single crystal of the protein that gave an X-ray diffraction structure within 0.96 Å.[6,7] Recently, we have synthesized a sulfur analogue of trigalacturonic acid (**1**, Fig. 1) as a mimetic substrate with tolerance against the enzymatic reaction.[8] It was designed to make a complex with *endo*-PG 1 to provide information for designing higher functional artificial mutants. Although the surface plasmon analysis suggested a stable complex with *endo*-PG 1, **1** failed to insert into the enzyme either by soaking or by co-crystallization experiments employing high concentrations of the compound. These results suggested that the interaction between **1** and the enzyme was not enough to form a complex by soaking experiments, and that **1** mimicked only the ground state form of the natural substrate; thus the compound is not suitable for complexation with the target enzyme. Analogues that mimic the transition state in the enzymatic reaction might be ideal for obtaining the stable complex with *endo*-PG 1. Based on this assumption, **2** was designed as the next analogue. A cyclohexene framework was introduced in place of the central pyranose ring by taking the structure of acarbose into account.[9–11] The cyclohexene ring was expected to reproduce the strained half-chair conformation of this ring at the transition state as shown in Figure 2.[12] Based on synthetic feasibility a thioether was employed for the linkage between the cyclohexene ring and the pyranose ring at the reducing end.

The hemiacetal function at the reducing end should cause the anomerization to give more than two chemical species, which made the thermochemical investigations more complex. The reducing end was fixed as the α-methyl glycoside.

2. Result and discussion

Phenyl 1-thio-β-D-galactopyranoside (**3**)[13] was converted to **4** in good yield by protecting successively with a trityl ether for the C6OH and methoxyphenylmethyl (MPM) ethers for C2, C3, and

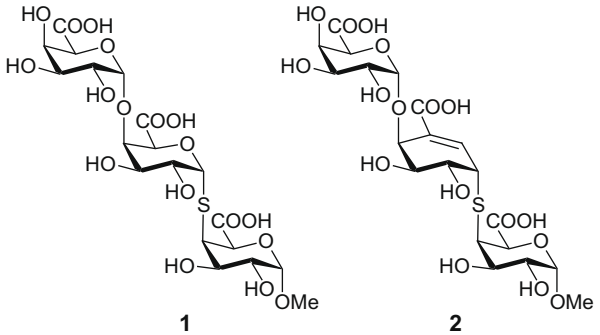

Figure 1. Trigalacturonic acid analogues.

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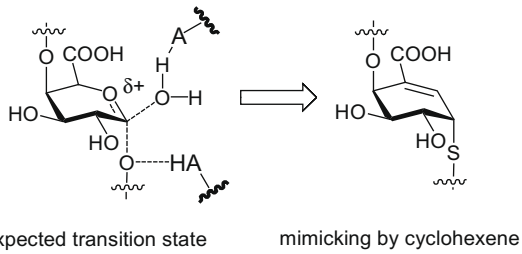
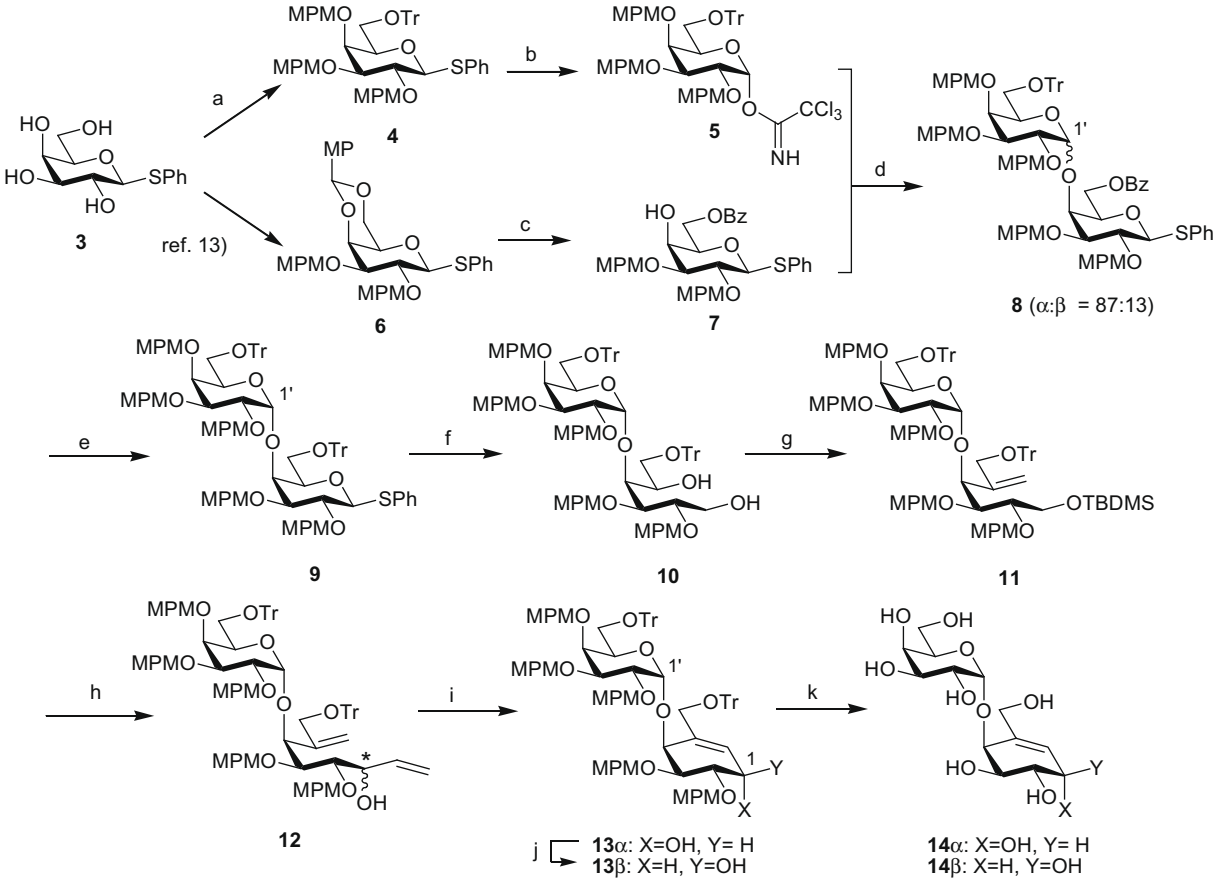


Figure 2. Stabilization of the strained transition state structure.

C4 hydroxy groups as shown in Scheme 1. After the phenylthio acetal group of **4** was removed by *N*-bromosuccinimide (NBS) under aqueous conditions, trichloroacetimidate was furnished at the anomeric hydroxy group to give a glycosyl donor **5** in 98% in two steps. On the other hand, the *p*-methoxybenzylidene acetal of **6** (prepared also from **3** by the established procedure)[14] was converted to acceptor **7** in 73% yield by acidic hydrolysis of the 4,6-*O*-*p*-methoxybenzylidene acetal, followed by selective benzoylation of the C6 primary hydroxy group at 0 °C.

Triethylsilyl trifluoromethanesulfonate (TESOTf) mediated glycosylation of **7** with the imidate **5** afforded disaccharide **8** in 92% yield as an inseparable mixture of α and β glycosides (α:β = 87:13 by NMR spectroscopy). Taking the latter operations into account, the benzoyl protective group was replaced with a trityl ether to give **9** in good yield. The minor β-isomer was removed with silica gel column chromatography after hydrolysis of the benzoyl ester. The resonance signal due to C1′H of **9** appeared at 4.93 ppm as a doublet (J = 2.5 Hz) in the ^{1}H NMR spectrum, which confirmed the α stereochemistry of the newly formed glycosyl linkage.

After the phenylthio ether in **9** was hydrolyzed by NBS–H_2O, and the anomeric moiety was reduced with sodium borohydride in a mixture of ethanol and dichloromethane to give diol **10** in 92% yield in two steps. Application of Halcomb's protocol[15] furnished the cyclohexene ring, affording **13** by the following sequential reactions to wit; (i) selective protection of the primary hydroxy group as the *tert*-butyldimethylsilyl (TBDMS) ether (98% yield), (ii) oxidation of the remaining alcohol using dimethyl sulfoxide/acetic anhydride (99% yield),[16] (iii) Tebbe olefination (→**11**, 65% yield),[17] (iv) cleavage of the TBDMS ether with tetrabutylammonium fluoride (98%), (v) Swern oxidation[18] of the liberated primary hydroxy group, (vi) addition of vinylmagnesium bromide to give **12** as an inseparable 10:7 mixture of diastereomers of the corresponding allylic alcohols (81% yield in two steps), and (vii) ring-closure olefin metathesis with Grubbs's second-generation reagent[19] (4 mol %) in toluene at 100 °C. The stereoisomers that resulted from the Grignard reaction were separated after the metathesis. A Mitsunobu reaction and the following basic hydrolysis inverted the C1OH group (*carbohydrate numbering*) of the undesired **13α** to converge into the desired **13β**.



Scheme 1. Reagents and conditions: (a) (1) TrCl, pyridine, 100 °C (97%), (2) MPMBr, NaH, DMF (72%); (b) (1) NBS, acetone–H_2O (99%), (2) CCl_3CN, DBU (99%); (c) (1) AcOH, H_2O, 60 °C (93%), (2) BzCl, Py, CH_2Cl_2, 0 °C (80%); (d) TESOTf, THF, MS4A, −20 °C (92%, α-glycoside:β-glycoside = 87:13 based on the ^{1}H NMR); (e) (1) 1 M NaOHaq, MeOH, CH_2Cl_2, then separation of anomers (74%), (2) TrCl, Py, 70 °C (98%); (f) (1) NBS, acetone–H_2O, 0 °C, (2) $NaBH_4$, EtOH, CH_2Cl_2, 92% (two steps); (g) (1) TBDMSCl, imidazole, DMF (98%), (2) DMSO, Ac_2O (99%), (3) Tebbe reagent, toluene, Py, −40→0 °C (65%); (h) (1) TBAF, THF (97%), (2) $(COCl)_2$, DMSO, Et_3N, CH_2Cl_2, −78 °C, (3) CH_2=CHMgBr, THF, −15→0 °C (81% in two steps, *R*:*S* = 7:10); (i) Grubbs II cat.(4 mol %), toluene, 100 °C then separation (**13α** 49%, **13β** 34%); (j) (1) *p*-nitrobenzoic acid, DEAD, PPh_3, THF, 0 °C→rt (96%), (2) NaOH, H_2O, MeOH, CH_2Cl_2 (92%); (k) (1) HCO_2H, MeOH, H_2O, 0 °C, (2) DDQ, H_2O, CH_2Cl_2 (**14α**: 48% from **13α**, **14β**: 55% from **13β**).

The stereochemistry at C1 was determined after removing all the protective groups (→**14α**, **14β**) due to serious ^{1}H NMR signal overlapping in **13α** and **13β**. The stereochemistry of **14α** could not be discussed directly because the C1H (*carbohydrate numbering*) was observed as a broad signal (4.29 ppm). However, the irradiation of C3H (4.08 ppm) resulted C2H to a doublet (3.96 ppm, $J_{C1H-C2H}$ = 4.1 Hz), which suggested a gauche orientation between the C1H and C2H. In contrast, that of **14β** was 7.3 Hz, which indicated a quasi-*anti* relationship between them. These were confirmed by NOE experiments. Characteristic NOE was observed between C1H (3.97 ppm) and C3H (3.51 ppm) in the case of **14β**, while the irradiation of C1H of **14α** induced signal enhancements at C2H and the olefinic proton (*C0H for convenience*). These observations established the stereochemistries of **14α** and **14β** as shown in Figure 3.

The sulfur atom was then introduced to the C1 (*carbohydrate numbering*) position of **13β** to afford thioacetate **15** in 98% in two steps (Scheme 2) by mesylation with methanesulfonic anhydride[20] and successive treatment with potassium thioacetate. Stereochemical inversion at the C1 position in this process was confirmed by the small coupling constant (4.9 Hz) between C1H and C2H in the ^{1}H NMR spectrum. The β-isomer of **15** was also prepared employing **13α** using similar treatments. The coupling constant between C1H and C2H for this sample was 6.6 Hz in the ^{1}H NMR spectrum at 50 °C, which indicated a quasi-anti relationship for these protons. Interestingly, the C1H signal appeared as broadened signal when the ^{1}H NMR spectrum was measured at 25 °C. The acetyl group in **15** was removed with hydrazine acetate to give thiol **16** in 84% yield.

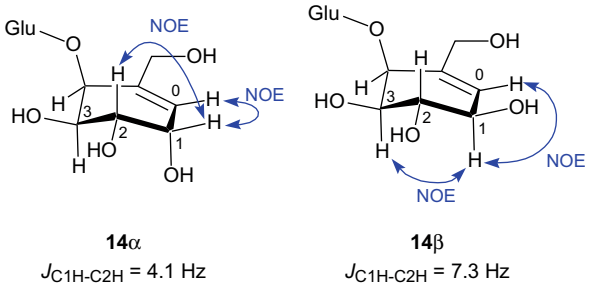
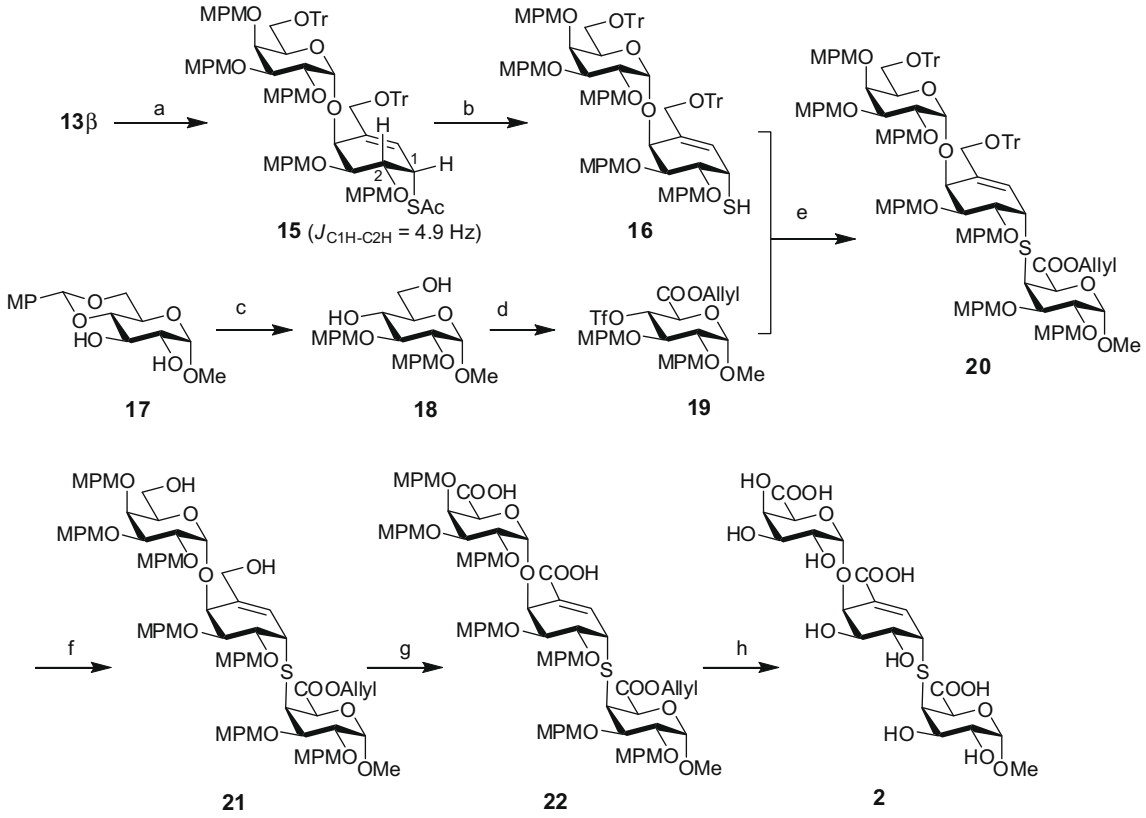


Figure 3. Coupling constants ($J_{C1H-C2H}$) and NOEs observed in **14α** and **14β**.

The coupling partner triflate **19** was also prepared. The known 4,6-*O*-protected α-methyl glucopyranoside (**17**)[21] was converted to diol **18** in 78% yield by MPM ether formation at the C2 and C3 hydroxy groups, and the successive acidic hydrolysis of the 4,6-*O*-*p*-methoxybenzylidene group. The primary hydroxy group of **18** was converted into the allyloxycarbonyl group in a moderate yield by oxidation with 2,2,6,6-tetramethylpiperadine 1-oxyl (TEMPO) in the presence of iodobenzene diacetate,[22,23] followed by allyl ester formation. In our preliminary experiments, we had experienced that alkaline treatment in the final step of the synthesis gave rise to an E2 type cleavage of the glycosidic bond. Thus, allyl ester was chosen as the protective group of the carboxylic acids with the expectation that it can be cleaved off under neutral conditions using palladium-catalyzed hydrolysis.

The remaining C4 hydroxy group was then activated in the form of a triflate to give **19** in 96% yield.

With thiol **16** and triflate **19** in hand, these units were connected. Treatment of **16** and **19** with sodium hydride in *N*,*N*-



Scheme 2. Reagents and conditions: (a) (1) Ms_2O, Et_3N, CH_2Cl_2, −20→0 °C, (2) KSAc, DMF (98% in two steps); (b) NH_2NH_2·AcOH, DMF, 0→10 °C (84%); (c) (1) MPMBr, NaH, DMF (81%), (2) AcOH, H_2O, 60 °C (96%); (d) (1) TEMPO, $PhI(OAc)_2$, CH_2Cl_2, H_2O (84%), (2) allyl alcohol, EDCI, HOBt, CH_2Cl_2, 0 °C→rt (68%), (3) Tf_2O, Py, CH_2Cl_2, 0 °C (96%); (e) NaH, DMF (36%); (f) HCOOH, H_2O, 0 °C→rt (73%); (g) (1) $(COCl)_2$, DMSO, Et_3N, CH_2Cl_2, −78 °C, (2) $NaClO_2$, NaH_2PO_4, 2-methyl-2-butene, *t*-BuOH, H_2O; (h) (1) $Pd(PPh_3)_4$, pyrrolidine, THF, (2) DDQ, CH_2Cl_2, H_2O, then ODS Sep-Pack (90% from **21**).

dimethylformamide resulted a thioether formation giving **20** in 36% yield along with recovered **16** (41%). Since this reaction accompanied the elimination of triflic acid or retro-Michael-type elimination of **16** from the product **20**, the starting **19** was not recovered. Two trityl groups in **20** were removed with aqueous formic acid to give diol **21** in 73% yield. Both liberated alcohol functions in **21** were oxidized into carboxylic acids in two steps (Swern oxidation followed by treatment with sodium chlorite), providing dicarboxylic acid **22**. It was found that **22** was less soluble, and the crude sample could not be purified by chromatography. Without purification, allyl and all MPM protective groups of **22** were cleaved successively by palladium tetrakistriphenylphosphine–pyrrolidine[24] and 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ), respectively, to give **2** in sufficient yield. Since **2** was readily soluble under aqueous conditions as expected, it was then purified by HPLC (Inertsil® DIOL, 10 × 250 mm, 10:90:0.01 H_2O–CH_3CN–TFA, 3.0 mL/min flow) to afford the sample (t_R = 50 min) in sufficient purity for enzymatic experiments. The ESIMS gave the protonated molecular ion signal at m/z = 573.1124 ($C_{20}H_{29}O_{17}S$, $[M+H]^+$: 573.1126) which proved that no oxidation occurred at the oxidation-labile sulfide function during these processes. Preliminary enzymatic studies revealed that **2** (0.3 mM) inhibited the hydrolysis of tetragalacturonic acid with *endo*-PG 1 by about 30%.

As described, we succeeded in synthesizing **2**, which was designed to mimic the transition state structure in the enzymatic hydrolysis of *endo*-PG 1. As expected, **2** showed the desired inhibition activity against the target enzyme. We and our collaborators are currently carrying out further investigations, such as calorimetric experiments and ES complex preparation, to study the proposed enzyme–inhibitor complex.

3. Experimental

3.1. 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. ^{1}H NMR spectra were obtained with a JEOL ALPHA 400 (400 MHz) and a JNM-ECA 500 (500 MHz) spectrometer. The chemical shifts are expressed in ppm downfield from the signal of trimethylsilane (0.00 ppm), which was used as an internal standard in the case of $CDCl_3$. When D_2O was employed, the remaining proton signal for HDO (4.63 ppm) was used as the internal standard. Apparent first-order splitting patterns are designated as s (*singlet*), d (*doublet*), t (*triplet*), m (*multiplet*), and br (*broad*). Some signals could not be assigned due to overlapping.

^{13}C NMR spectra were recorded also on a JEOL ALPHA 400 (100 MHz) and a JNM-ECA 500 (125 MHz) spectrometer. The isotope ^{13}C in the solvents was used as the internal standard ($^{13}CDCl_3$; 77.0 ppm). For ^{13}C NMR spectra in D_2O, the default offset was employed and not corrected. Assignments of the signals were according to the numbering based on IUPAC nomenclature if not mentioned. For carbohydrate derivatives, numberings based on carbohydrate nomenclature are employed. Measurements of IR spectra were carried out with a HORIBA FT-720 Fourier transform infrared spectrometer on a KBr cell. Measurements of field desorption (FD) and fast atom bombardment (FAB) mass spectra were performed on a JEOL JMS AX500. Electrospray-ionization mass spectra were obtained by a HITACHI NanoFrontier LD spectrometer. MS analyses for unstable compounds such as glycosyl imidates were not performed. Analytical and preparative thin-layer chromatography was carried out using precoated silica gel plates, E. Merck Silica Gel 60F_{254} (Art. 1.05715). E. Merck Silica Gel 60 (Art. 1.07734) was used for column chromatography. Medium-pressure column chromatography was performed employing a Yamazene ULTRA PACK SI-40B. All reactions were carried out under an N_2 or Ar atmosphere using dried solvents, except for those conducted under aqueous conditions. Dichloromethane and tetrahydrofuran were freshly distilled from diphosphorus pentoxide and benzophenone-ketyl, respectively.

3.2. Phenyl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-1-thio-6-*O*-triphenylmethyl-β-D-galactopyranoside (4)

A solution of phenyl 1-thio-β-D-galactopyranoside (**3**)[13] (2.0 g, 7.34 mmol) in pyridine (10 mL) was stirred with triphenylchloromethane at 100 °C for 30 min. The mixture was poured into H_2O (100 mL), and the aqueous layer was extracted with EtOAc (70 mL × 3). The combined organic layer was washed with brine (100 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (70:30 EtOAc–hexane) gave phenylthio 6-*O*-triphenylmethyl-β-D-galactopyranoside (3.68 g, 97%) as an oil: $[\alpha]_D^{23}$ −11.2 (*c* 1.21, $CHCl_3$); IR (film) 3425, 2925, 1445, 1090, 1060, 1030, 910, 740, 705 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.86 (d, 1H, *J* = 4.6 Hz, C4O*H*), 3.20 (d, 1H, *J* = 2.5 Hz, C2O*H*), 3.32 (dd, 1H, *J* = 7.2, 12.7 Hz, C6*H*H), 3.43–3.53 (4H, C3O*H*, C6*H*H, C3*H*, C5*H*), 3.66 (dt, 1H, *J* = 2.5, 9.7 Hz, C2*H*), 3.88 (br t, 1H, *J* = 4.6 Hz, C4*H*), 4.51 (d, 1H, *J* = 9.7 Hz, C1*H*), 7.18–7.28 (12H, *aromatic protons*), 7.44 (16H, *aromatic protons*), 7.58 (2H, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 63.55 (*C*6), 69.63 (*C*4), 69.93 (*C*2), 74.84 (*C*3), 77.62 (*C*5), 87.05 (*C*Ph_3), 88.55 (*C*1), 127.11, 127.72, 127.90, 128.63, 128.93, 132.11, 132.80, 143.64 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 537 (70, $[M+Na]^+$), 243 (100, $[CPh_3]^+$); HRESIMS: calcd for $C_{31}H_{30}O_5SNa$ $[M+Na]^+$, 537.1712; found, *m*/*z* 537.1740.

Sodium hydride (washed with hexane, 1.20 g, 50.0 mmol) was added slowly to a DMF solution (40 mL) of the product (4.36 g, 8.47 mmol) at room temperature. Upon the addition of the substrate, H_2 gas evolved. After stirring for 10 min, 4-methoxybenzyl bromide[25] (14.6 g, 72.6 mmol) was added at 0 °C. After stirring at 0 °C for 10 min, the cooling bath was removed, and the mixture was stirred at room temperature for 1 h. Methanol (4.0 mL) and Et_3N (2.0 mL) were successively added to decompose the excess reagent. After stirring for additional 30 min, the mixture was poured into H_2O (200 mL), and the aqueous layer was extracted with EtOAc (150 mL × 3). The organic layers were washed successively with H_2O (300 mL) and brine (200 mL), combined, dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified with silica gel column chromatography (16:84 EtOAc–hexane) to give **4** (5.30 g, 72%) as an oil: $[\alpha]_D^{23}$ +28.7 (*c* 0.870, $CHCl_3$); IR (film) 2930, 1610, 1510, 1250, 1085, 1030, 820, 745, 705 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.15 (dd, 1H, *J* = 6.3, 9.7 Hz, C6*H*H), 3.29 (br t, 1H, *J* = 6.3 Hz, C5*H*), 3.47 (dd, 1H, *J* = 2.8, 9.4 Hz, C3*H*), 3.55 (dd, 1H, *J* = 6.3, 9.7 Hz, C6*H*H), 3.78 (s, 6H, OCH_3 × 2), 3.79 (s, 3H, OCH_3), 3.79 (br d, 1H, *J* = 2.8 Hz, C4*H*), 3.85 (t, 1H, *J* = 9.4 Hz, C2*H*), 4.44 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.57 (d, 1H, *J* = 9.4 Hz, C1*H*), 4.62 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.64 (d, 1H, *J* = 10.0 Hz, ArC*H*HO), 4.66 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.70 (d, 1H, *J* = 10.0 Hz, ArC*H*HO), 4.76 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 6.74 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.85 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.86 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 7.03 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.14 (3H, *aromatic protons*), 7.20–7.31 (13H, *aromatic protons*), 7.39 (6H, *aromatic protons*), 7.54 (2H, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.24 (OCH_3 × 2), 55.26 (OCH_3), 63.20 (*C*6), 72.52 (ArCH_2O), 73.56 (*C*4), 73.67, 75.21 (each ArCH_2O), 77.12 (*C*2), 77.72 (*C*5), 83.91 (*C*3), 86.91 (*C*Ph_3), 87.74 (*C*1), 113.44, 113.73, 113.79, 126.69, 126.99, 127.80, 128.64, 128.72, 129.17, 129.38, 129.96, 130.51, 130.60, 130.82, 130.89, 174.68, 143.90, 158.93, 159.21, 159.27 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 897 (100, $[M+Na]^+$), 243 (27,

$[CPh_3]^+$); HRESIMS: calcd for $C_{55}H_{54}O_8SNa$ $[M+Na]^+$, 897.3437; found, *m*/*z* 897.3427.

3.3. 2,3,4-Tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-β-D-galactopyranosyl 2,2,2-trichloroacetimidate (5)

A solution of **4** (1.85 g, 2.11 mmol) in a mixture of acetone (40 mL) and H_2O (4.0 mL) was stirred with NBS (934 mg 5.25 mmol) at 0 °C. After 5 min, 10% $Na_2S_2O_3$ (4.0 mL) and satd aq $NaHCO_3$ (20 mL) were added to the mixture. Acetone was removed in vacuo, and the resulting aqueous solution was extracted with EtOAc (150 mL × 3). The combined organic layer was washed with brine (100 mL), dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified with silica gel column chromatography (26:74 EtOAc–hexane) to give 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-D-galactopyranose (1.63 g, 99%) as an oil: $[\alpha]_D^{23}$ +31.3 (*c* 1.08, $CHCl_3$); IR (film) 3435, 2930, 1610, 1510, 1250, 1080, 1035, 820, 705 cm^{-1}; The ^1H NMR spectrum indicated that the sample consisted of a mixture of anomers (α:β = 80:20 in $CDCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 2.86 (d, 1H × 0.8, *J* = 2.0 Hz, C1O*H* (α-anomer)), 2.93 (d, 1H × 0.2, *J* = 7.0 Hz, C1O*H* (β-anomer)), 3.16 (dd, 1H × 0.8, *J* = 7.7, 9.0 Hz, C6*H*H (α-anomer)), 3.26 (dd, 1H × 0.2, *J* = 7.4, 8.8 Hz, C6*H*H (β-anomer)), 3.37 (dd, 1H × 0.8, *J* = 5.7, 9.0 Hz, C6*H*H (α-anomer)), 3.39 (1H × 0.2, C5*H* (β-anomer)), 3.45 (1H × 0.2 × 2, C3*H* (β-anomer), C6*H*H (β-anomer)), 3.62 (dd, 1H × 0.2, *J* = 7.0, 9.6 Hz, C2*H* (β-anomer)), 3.76 (s, 3H × 0.8, OCH_3 (α-anomer)), 3.76 (s, 3H × 0.2, OCH_3 (β-anomer)), 3.77 (s, 3H × 0.8, OCH_3 (α-anomer)), 3.78 (s, 3H × 0.2, OCH_3 (β-anomer)), 3.80 (s, 3H × 0.2, OCH_3 (β-anomer)), 3.80 (s, 3H × 0.8, OCH_3 (α-anomer)), 3.85 (dd, 1H × 0.8, *J* = 2.6, 10.0 Hz, C3*H* (α-anomer)), 3.88 (br d, 1H × 0.2, *J* = 2.5 Hz, C4*H* (β-anomer)), 3.91 (dd, 1H × 0.8, *J* = 3.3, 10.0 Hz, C2*H* (α-anomer)), 3.97 (br d, 1H × 0.8, *J* = 2.6 Hz, C4*H* (α-anomer)), 4.10 (br dd, 1H × 0.8, *J* = 5.7, 7.7 Hz, C5*H* (α-anomer)), 4.35 (d, 1H × 0.8, *J* = 10.8 Hz, ArC*H*HO (α-anomer)), 4.41 (d, 1H × 0.2, *J* = 10.9 Hz, ArC*H*HO (β-anomer)), 4.54 (t, 1H × 0.2, *J* = 7.0 Hz, C1*H* (β-anomer)), 4.58–4.80 (5H, ArC*H*HO × 5), 5.15 (dd, 1H × 0.8, *J* = 2.0, 3.3 Hz, C1*H* (α-anomer)), 6.69–7.40 (27H, *aromatic protons*).

A solution of the product (1.63 g, 2.08 mmol) in CH_2Cl_2 (10 mL) was stirred with CCl_3CN (600 mg, 4.16 mmol) in the presence of DBU (32.0 mg, 210 μmol) at −15 °C for 20 min. After concentration in vacuo, the residue was purified with silica gel column chromatography (20:80 EtOAc–hexane) to give **5** (1.90 g, 99%) as an oil. The ^1H NMR spectrum indicated that the sample consisted of a mixture of anomers (α:β = 5:1). Assignments for signals of the major isomer and some of the minor isomers were only described. ^1H NMR (400 MHz, $CDCl_3$) δ 3.09 (dd, 1H × 0.83, *J* = 6.5, 9.2 Hz, C6*H*H (α-anomer)), 3.13 (dd, 1H × 0.17, *J* = 5.7 8.8 Hz, C6*H*H (β-anomer)), 3.41 (dd, 1H × 0.83, *J* = 6.5, 9.2 Hz, C6*H*H (α-anomer)), 3.51 (3H × 0.17, C6*H*H (β-anomer), C5*H* (β-anomer), C3*H* (β-anomer)), 3.76, 3.78, 3.81 (each s, 3H × 0.83, OCH_3 (α-anomer)), 3.83 (br d, 1H × 0.17, *J* = 3.1 Hz, C4*H* (β-anomer)), 3.98 (dd, 1H × 0.83, *J* = 2.7, 10.0 Hz, C3*H* (α-anomer)), 4.03 (br d, 1H × 0.83, *J* = 2.7 Hz, C4*H* (α-anomer)), 4.12 (dd, 1H × 0.83, *J* = 3.6, 10.0 Hz, C2*H* (α-anomer)), 4.19 (br t, 1H × 0.83, *J* = 6.5 Hz, C5*H* (α-anomer)), 4.42 (d, 1H × 0.83, *J* = 10.8 Hz, ArC*H*HO (α-anomer)), 4.62, 4.66 (each d, 1H × 0.83, *J* = 11.2 Hz, ArCH_2O (α-anomer)), 4.67 (d, 1H × 0.83, *J* = 11.5 Hz, ArC*H*HO (α-anomer)), 4.73 (d, 1H × 0.83, *J* = 10.8 Hz, ArC*H*HO (α-anomer)), 4.78 (d, 1H × 0.83, *J* = 11.5 Hz, ArC*H*HO (α-anomer)), 5.70 (d, 1H × 0.17, *J* = 8.0 Hz, C1*H* (β-anomer)), 6.45 (d, 1H × 0.83, *J* = 3.6 Hz, C1*H* (α-anomer)), 6.70 (br d, 2H × 0.83, *J* = 8.7 Hz, *aromatic protons* (α-anomer)), 6.81 (br d, 2H × 0.83, *J* = 8.7 Hz, *aromatic protons* (α-anomer)), 6.87 (br d, 2H × 0.83, *J* = 8.7 Hz, *aromatic protons* (α-anomer)), 6.97 (br d, 2H × 0.83, *J* = 8.6 Hz, *aromatic protons* (α-anomer)), 7.22–7.41 (19H × 0.83, *aromatic protons* (α-anomer)), 8.53 (s, 1H × 0.83, C(=N*H*)CCl_3 (α-anomer)), 8.64 (s, 1H × 0.17, C(=N*H*)CCl_3 (β-anomer)). This sample gradually decomposed, so it was immediately used for the next step.

3.4. Phenyl 2,3-di-*O*-(4-methoxyphenylmethyl)-4,6-*O*-(4-methoxyphenylmethylidene)-1-thio-β-D-galactopyranoside (6)

A solution of **3** (2.62 g, 9.62 mmol) in DMF (20 mL) was stirred with 4-methoxybenzaldehyde dimethylacetal (3.50 g, 19.2 mmol) and camphorsulfonic acid (22.3 mg, 96.0 μmol) at 100 °C for 10 min. After cooling, the mixture was poured into 5% aq $NaHCO_3$ (100 mL), and the aqueous layer was extracted with EtOAc (70 mL × 3). The extracts were washed with H_2O (50 mL) and brine (50 mL), combined, dried over $MgSO_4$, and then concentrated in vacuo. Recrystallization of the crude solid from 30:70 EtOAc–hexane gave phenyl 4,6-*O*-(4-methoxyphenylmethylidene)-1-thio-β-D-galactopyranoside (2.74 g, 72%) as needles: mp 151–154 °C; $[\alpha]_D^{23}$ −7.50 (*c* 1.50, $CHCl_3$); IR (KBr) 3410, 2910, 1615, 1515, 1250, 1165, 825 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.48 (br d, 1H, *J* = 9.0 Hz, C2O*H*), 2.51 (d, 1H, *J* = 1.2 Hz, C3O*H*), 3.55 (br dd, 1H, *J* = 1.4, 1.7 Hz, C5*H*), 3.69 (m, 2H, C2*H*, C3*H*), 3.82 (s, 3H, OCH_3), 4.02 (dd, 1H, *J* = 1.7, 12.4 Hz, C6*H*H), 4.20 (br d, 1H, *J* = 1.9, C4*H*), 4.37 (dd, 1H, *J* = 1.4, 12.4 Hz, C6*H*H), 4.51 (m, 1H, C1*H*), 5.47 (s, 1H, ArC*H*), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.33 (m, 5H, *aromatic protons*), 7.69 (br dd, 2H, *J* = 2.0, 8.2 Hz, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.33 (OCH_3), 68.86 (*C*2), 69.25 (*C*6), 70.06 (*C*5), 73.82 (*C*3), 75.30 (*C*4), 87.00 (*C*1), 101.29 (Ar*C*$(OR)_2$), 113.57, 127.82, 128.21, 128.93, 130.14, 130.71, 133.76, 160.33 (*aromatic carbons*); negative-ion FABMS (%, rel. int.) *m*/*z*: 389 (2.1, $[M-H]^-$), 375 (1.3, $[M-CH_3]^-$), 148 (100), 109 (91, $[PhS]^-$); negative-ion HRFABMS: calcd for $C_{20}H_{21}O_8S$ $[M-H]^-$, 389.1059; found, *m*/*z* 389.1057.

Sodium hydride (washed with hexane, 789 mg, 32.9 mmol) was slowly added to a DMF solution (20 mL) of the product (3.21 g, 8.22 mmol) at room temperature. Upon the addition of the substrate, H_2 gas evolved. After stirring for 30 min, 50% toluene solution of MPMBr (13.2 g, 32.8 mmol) was added at 0 °C. The cooling bath was removed after 10 min, and the mixture was stirred at room temperature for additional 30 min. Methanol (5.0 mL) and triethylamine (5.0 mL) were added to decompose the excess reagent. After stirring for an additional 30 min, the mixture was poured into H_2O (100 mL), and the aqueous layer was extracted with EtOAc (70 mL × 3). The organic layers were successively washed with H_2O (50 mL) and brine (50 mL), combined, and dried over $MgSO_4$. After concentration, the residue was purified with silica gel column chromatography (25:75 EtOAc–hexane) to give **6** (4.98 g, 96%) as an oil: $[\alpha]_D^{23}$ +1.7 (*c* 1.25, $CHCl_3$); IR (film) 2860, 1610, 1515, 1250, 1170, 1100, 1035, 820 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.37 (br dd, 1H, *J* = 1.3, 1.4 Hz, C5*H*), 3.57 (dd, 1H, *J* = 3.3, 9.2 Hz, C3*H*), 3.79, 3.80, 3.83 (each s, 3H, OCH_3), 3.86 (t, 1H, *J* = 9.2 Hz, C2*H*), 3.95 (dd, 1H, *J* = 1.4, 12.4 Hz, C6*H*H), 4.10 (br d, 1H, *J* = 3.3 Hz, C4*H*), 4.33 (dd, 1H, *J* = 1.3, 12.4 Hz, C6*H*H), 4.58 (d, 1H, *J* = 9.2 Hz, C1*H*), 4.62 (s, 2H, ArCH_2O), 4.63, 4.66 (each d, 1H, *J* = 12.3 Hz, ArC*H*HO), 5.43 (s, 1H, ArC*H*), 6.82 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.87 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.91 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 7.16–7.27 (m, 5H, *aromatic protons*), 7.33 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.44 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.70 (br dd, 2H, *J* = 2.1, 7.8 Hz, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.24, 55.27, 55.34 (each OCH_3), 69.37 (*C*6), 69.84 (*C*5), 71.46 (Ar*C*H_2O), 73.79 (*C*4), 75.05 (Ar*C*H_2O), 75.18 (*C*2), 80.95 (*C*3), 86.59 (*C*1), 101.24 (Ar*C*$(OR)_2$), 113.49, 113.73, 113.76, 127.36, 127.91, 128.82, 129.37, 129.81, 130.23, 130.57, 130.76, 132.67, 132.88, 159.25, 159.27, 160.14 (*aromatic carbons*); FDMS (%, rel. int.) *m*/*z*: 631 (38, $[M+H]^+$), 630 (100, $[M]^+$); HRFDMS: calcd for $C_{36}H_{38}O_8S$ $[M]^+$, 630.2287; found, *m*/*z* 630.2276.

3.5. Phenyl 6-*O*-benzoyl-2,3-di-*O*-(4-methoxyphenylmethyl)-1-thio-β-D-galactopyranoside (7)

A solution of **6** (3.50 g, 5.55 mmol) in 90% aq acetic acid solution (100 mL) was stirred at 60 °C for 10 min. After cooling, the mixture was concentrated in vacuo below 40 °C to give a crude solid. Recrystallization from 4:6 EtOAc–hexane gave phenyl 2,3-di-*O*-(4-methoxyphenylmethyl)-1-thio-β-D-galactopyranoside (2.65 g, 93%) as needles: mp 113 °C; $[\alpha]_D^{24}$ +7.5 (*c* 1.24, $CHCl_3$); IR (film) 3435, 2930, 1610, 1510, 1250, 1085, 1035, 820 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.14 (br, 1H, C6O*H*), 2.60 (br, 1H, C4O*H*), 3.47 (ddd, 1H, *J* = 0.8, 4.2, 6.8 Hz, C5*H*), 3.55 (dd, 1H, *J* = 3.3, 8.9 Hz, C3*H*), 3.71 (t, 1H, *J* = 8.9 Hz, C2*H*), 3.77 (1H, C6*H*H), 3.80, 3.81 (each s, 3H, OCH_3), 3.96 (br dd, 1H, *J* = 6.8, 11.8 Hz, C6*H*H), 4.00 (br dd, 1H, *J* = 0.8, 3.3 Hz, C4*H*), 4.63 (d, 1H, *J* = 8.9 Hz, C1*H*), 4.64 (s, 2H, ArCH_2O), 4.67. 4.75 (each d, 1H, *J* = 10.0 Hz, ArC*H*HO), 6.87 (4H, *aromatic protons*), 7.25–7.34 (7H, *aromatic protons*), 7.55 (2H, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.27, 55.29 (each OCH_3), 62.77 (*C*6), 67.41 (*C*4), 72.00, 75.37 (each ArCH_2O), 76.69 (*C*2), 78.02 (*C*5), 82.06 (*C*3), 87.59 (*C*1), 113.80, 113.98, 127.42, 128.93, 129.55, 129.64, 129.89, 130.33, 131.77, 133.71, 159.38, 159.52 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 535.1756 (21, calcd for $C_{28}H_{32}O_7SNa$ $[M+Na]^+$: 535.1766), 530.2199 (100, calcd for $C_{28}H_{36}NO_7S$ $[M+NH_4]^+$: 530.2212).

Benzoyl chloride (829 mg, 5.90 mmol) was added to a mixture of the product (3.00 g, 5.85 mmol) and pyridine (933 mg, 11.8 mmol) in CH_2Cl_2 (7.0 mL) at 0 °C. After stirring at the same temperature for 1 h, the mixture was poured into H_2O (100 mL), and the aqueous layer was extracted with EtOAc (70 mL × 3). The combined organic layer was washed with brine (100 mL), dried over $MgSO_4$, and then concentrated in vacuo. Recrystallization of the residue from 30:70 EtOAc–hexane gave **7** (2.90 g, 80%) as needles: mp 153 °C; $[\alpha]_D^{25}$ +1.9 (*c* 1.14, $CHCl_3$); IR (film) 3500, 2905, 1705, 1510, 1295, 1250, 1120, 1090, 1050, 1030, 810, 715 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.50 (dd, 1H, *J* = 1.2, 2.4 Hz, C4O*H*), 3.57 (dd, 1H, *J* = 3.4, 9.0 Hz, C3*H*), 3.72 (t, 1H, *J* = 9.0 Hz, C2*H*), 3.77 (1H, C5*H*), 3.79, 3.80 (each s, 3H, OCH_3), 4.01 (1H, C4*H*), 4.56 (dd, 1H, *J* = 7.7, 10.6 Hz, C6*H*H), 4.63 (1H, C6*H*H), 4.63 (d, 1H, *J* = 9.0 Hz, C1*H*), 4.64, 4.67 (each d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.68, 4.79 (each d, 1H, *J* = 10.0 Hz, ArC*H*HO), 6.87 (4H, *aromatic protons*), 7.15 (3H, *aromatic protons*), 7.26 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 7.34 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 7.48 (br t, 3H, *J* = 7.5 Hz, *aromatic protons*), 7.53–7.61 (3H, *aromatic protons*), 8.02 (br dd, 2H, *J* = 1.3, 8.4 Hz, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.25, 55.28 (each OCH_3), 64.01 (*C*6), 67.02 (*C*4), 72.20, 75.44 (each ArCH_2O), 75.82 (*C*5), 76.75 (*C*2), 81.90 (*C*3), 87.94 (*C*1), 113.80, 113.98, 127.23, 128.38, 128.77, 129.55, 129.64, 129.74, 129.84, 129.92, 130.30, 131.56, 133.13, 134.13, 159.39, 159.53 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 639.2020 (15, calcd for $C_{35}H_{36}O_8SNa$ $[M+Na]^+$: 639.2029), 634.2464 (100, calcd for $C_{28}H_{40}NO_8S$ $[M+NH_4]^+$: 634.2475).

3.6. Phenyl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-6-*O*-benzoyl-2,3-di-*O*-(4-methoxyphenylmethyl)-1-thio-β-D-galactopyranoside (8)

Triethylsilyl trifluoromethanesulfonate (85 μg, 0.32 μmol) was added at −20 °C to a suspension of a mixture of **7** (1.00 g, 1.62 mmol), **5** (3.00 g, 3.24 mmol), and powdered and freshly activated molecular sieves 4 A (100 mg) in THF (30 mL). After stirring for 5 min, Et_3N (50 μL) was added to quench the reaction. The mixture was filtered through a cotton pad, and the filtrate was concentrated in vacuo. Purification of the residue with silica gel column chromatography (20:80 EtOAc–hexane) gave **8** (2.06 g, 92%) as a mixture of anomers (α-isomer:β-isomer = 87:12). $[\alpha]_D^{24}$ +13.2 (*c* 1.80, $CHCl_3$); IR (film) 2930, 1720, 1610, 1510, 1250, 1170, 1090, 1035, 820, 710 cm^{-1}. The ^1H NMR spectrum indicated that the sample consisted of a mixture of anomers (α:β = 87:13). Assignments for signals of the major isomer and only some of the minor isomer are described. ^1H NMR (400 MHz, $CDCl_3$) δ 3.22 (t, 1H × 0.87, *J* = 8.4 Hz, C6′*H*H (α-isomer)), 3.36 (dd, 1H × 0.87, *J* = 5.1, 8.4 Hz, C6′*H*H (α-isomer)), 3.39 (dd, 1H × 0.87, *J* = 2.5, 9.4 Hz, C3*H* (α-isomer)), 3.44 (dd, 1H × 0.13, *J* = 5.3, 9.2 Hz, C6′*H*H (β-isomer)), 3.52 (dd, 1H × 0.13, *J* = 2.7, 9.3 Hz, C3*H* (β-isomer)), 3.63 (s, 3H × 0.87, OCH_3 (α-isomer)), 3.64 (1H × 0.87, C5*H* (α-isomer)), 3.709 (s, 3H × 0.13, OCH_3 (β-isomer)), 3.713 (s, 3H × 0.87, OCH_3 (α-isomer)), 3.75, 3.77 (each s, 3H × 0.13, OCH_3 (β-isomer)), 3.78 (s, 6H × 0.87, OCH_3 × 2 (α-isomer)), 3.78 (1H × 0.87, C2*H* (α-isomer)), 3.80 (s, 3H × 0.87, OCH_3 (α-isomer)), 3.81 (s, 3H × 0.13, OCH_3 (β-isomer)), 3.85 (br d, 1H × 0.87, *J* = 2.5 Hz, C4*H* (α-isomer)), 4.01 (dd, 1H × 0.87, *J* = 3.4, 10.2 Hz, C2′*H* (α-isomer)), 4.08 (dd, 1H × 0.87, *J* = 2.5, 10.2 Hz, C3′*H* (α-isomer)), 4.23 (br d, 1H × 0.87, *J* = 2.5 Hz, C4′*H* (α-isomer)), 4.31 (br d, 1H × 0.13, *J* = 2.3 Hz, C4*H* (β-isomer)), 4.37 (d, 1H × 0.87, *J* = 10.2 Hz, ArC*H*HO (α-isomer)), 4.38, 4.42 (each d, 1H × 0.87, *J* = 12.3 Hz, ArC*H*HO (α-isomer)), 4.46 (br dd, 1H × 0.87, *J* = 5.1, 8.4 Hz, C5′*H* (α-isomer)), 4.60 (d, 1H × 0.87, *J* = 9.7 Hz, C1*H* (α-isomer)), 4.60–4.72 (5H × 0.87, C6H_2 (α-isomer), ArC*H*HO (α-isomer), ArCH_2O (α-isomer)), 4.75 (d, 1H × 0.87, *J* = 10.2 Hz, ArC*H*HO (α-isomer)), 4.81 (d, 1H × 0.87, *J* = 10.2 Hz, ArC*H*HO (α-isomer)), 4.813 (s, 2H × 0.87, ArCH_2O (α-isomer)), 4.91 (d, 1H × 0.87, *J* = 3.4 Hz, C1′*H* (α-isomer)), 4.94 (d, 1H × 0.13, *J* = 11.0 Hz, ArC*H*HO (β-isomer)), 6.66–7.59 (43H, *aromatic protons*), 7.96 (br dd, 2H × 0.87, *J* = 1.3, 8.1 Hz, *aromatic protons* (α-isomer)), 7.99 (br dd, 2H × 0.13, *J* = 1.3, 8.1 Hz, *aromatic protons* (β-isomer)); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.02, 55.12, 55.23, 55.25, 55.28 (each OCH_3), 62.16 (*C*6′), 63.64 (*C*6), 70.60 (*C*5′), 71.72, 72.20, 73.51, 74.20, 75.13 (each ArCH_2O), 75.15 (*C*4′), 75.83 (*C*2′, *C*4), 76.43 (*C*5), 76.85 (*C*2), 79.14 (*C*3′), 81.11 (*C*3), 86.67 (*C*Ph_3), 87.86 (*C*1), 100.75 (*C*1′), 113.39, 113.62, 113.67, 113.71, 113.79, 126.99, 127.79, 128.40, 128.76, 128.94, 129.36, 129.51, 129.65, 129.74, 129.97, 130.52, 130.60, 131.01, 131.10, 131.21, 133.04, 134.71, 143.84, 158.89, 159.02 (×2), 159.04, 159.23 (*aromatic carbons*), 166.09 (*C*=O); ESIMS (%, rel. int.) *m*/*z*: 1403.5384 (34, calcd for $C_{84}H_{84}O_{16}SNa$ $[M+Na]^+$: 1403.5378), 1398.5817 (100, calcd for $C_{84}H_{88}NO_{16}S$ $[M+NH_4]^+$: 1398.5824).

3.7. Phenyl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-2,3-di-*O*-(4-methoxyphenylmethyl)-1-thio-6-*O*-triphenylmethyl-β-D-galactopyranoside (9)

A solution of **8** (2.20 g, 1.59 mmol) in a mixture of MeOH (50 mL) and CH_2Cl_2 (50 mL) was stirred with 1.0 M aq NaOH (4 mL) at room temperature for 5 h. After the MeOH was removed in vacuo, the resulting aqueous solution was diluted with H_2O (100 mL), and the aqueous layer was extracted with EtOAc (80 mL × 3). The combined organic layer was washed with brine (100 mL), dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue with silica gel column chromatography (30:70 EtOAc–hexane) gave phenyl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-2,3-di-*O*-(4-methoxyphenylmethyl)-1-thio-β-D-galactopyranoside (1.50 g, 74%) as an oil: $[\alpha]_D^{24}$ +13.5 (*c* 0.850, $CHCl_3$); IR (film) 3430, 2935, 1610, 1510, 1250, 1085, 1035, 820, 705 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 3.13 (dd, 1H, *J* = 7.6, 8.6 Hz, C6′*H*H), 3.36 (dd, 1H, *J* = 5.4, 8.6 Hz, C6′*H*H), 3.43 (dd, 1H, *J* = 2.6, 9.6 Hz, C3*H*), 3.51 (1H, C5*H*), 3.66 (1H, C6*H*H), 3.725 (t, 1H, *J* = 9.6 Hz, C2*H*), 3.73 (s, 3H, OCH_3), 3.76–3.80 (11H, C6*H*H, C6O*H*, OCH_3 × 3), 3.81 (s, 3H, OCH_3), 3.99 (dd, 1H, *J* = 3.1, 9.6 Hz, C2′*H*), 4.02 (br d, 1H, *J* = 2.6 Hz, C4*H*), 4.03–4.06 (2H, C3′*H*, C4′*H*), 4.29 (br dd, 1H, *J* = 5.4, 7.6 Hz, C5′*H*), 4.34 (d, 1H, *J* = 10.6 Hz, ArC*H*HO), 4.41 (d,

1H, *J* = 9.9 Hz, ArC*H*HO), 4.46 (d, 1H, *J* = 12.3 Hz, ArC*H*HO), 4.47 (d, 1H, *J* = 9.9 Hz, ArC*H*HO), 4.49 (d, 1H, *J* = 12.3 Hz, ArC*H*HO), 4.58 (d, 1H, *J* = 11.4 Hz, ArC*H*HO), 4.62 (d, 1H, *J* = 9.6 Hz, C1*H*), 4.71 (d, 1H, *J* = 11.6 Hz, ArC*H*HO), 4.73 (d, 1H, *J* = 10.6 Hz, ArC*H*HO), 4.75 (d, 1H, *J* = 11.6 Hz, ArC*H*HO), 4.80 (d, 1H, *J* = 11.4 Hz, ArC*H*HO), 5.00 (d, 1H, *J* = 3.1 Hz, C1′*H*), 6.73 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.74 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.79 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.81 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.93 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.99 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.10–7.16 (8H, *aromatic protons*), 7.20–7.24 (10H, *aromatic protons*), 7.35–7.38 (8H, *aromatic protons*), 7.56 (br dd, 2H, *J* = 1.3, 8.4 Hz, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.12, 55.18 (each O*C*H$_3$), 55.24 (OCH$_3$ × 2), 55.28 (O*C*H$_3$), 59.89 (*C*6), 62.83 (*C*6′), 71.06 (*C*5′), 72.26, 72.31, 74.25, 74.40 (each Ar*C*H$_2$O), 74.53 (*C*4), 75.21 (Ar*C*H$_2$O), 75.41 (*C*4′), 77.32 (*C*2′), 77.49 (*C*2), 77.74 (*C*5), 78.46 (*C*3′), 82.62 (*C*3), 86.59 (*C*Ph$_3$), 88.15 (*C*1), 99.71 (*C*1′), 113.41, 113.56, 113.68, 113.92, 113.98, 126.96, 127.14, 127.78, 128.76, 128.89, 129.04, 129.08, 129.35, 129.59, 129.69, 130.31(×2), 130.55, 130.62, 130.89, 131.17, 134.59, 143.78, 158.95, 159.00, 159.09, 159.21, 159.58 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1299.5126 (22, calcd for $C_{77}H_{80}O_{15}SNa$ $[M+Na]^+$: 1299.5116), 1294.5562 (100, calcd for $C_{77}H_{84}NO_{15}S$ $[M+NH_4]^+$: 1294.5562).

A solution of the product (4.20 g, 3.29 mmol) in pyridine (30 mL) was stirred with chlorotriphenylmethane (1.80 g, 6.46 mmol) at 100 °C for 1.5 h. The mixture was poured into H_2O (200 mL), and the aqueous layer was extracted with EtOAc (150 mL × 3). The combined organic layer was washed with brine (150 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (24:76 EtOAc–hexane) gave **9** (4.90 g, 98%) as an oil: $[\alpha]_D^{24}$ +17.5 (*c* 1.13, $CHCl_3$); IR (film) 2930, 1610, 1510, 1445, 1245, 1170, 1090, 1035, 820, 730, 705 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.53 (br t, 1H, *J* = 6.6 Hz, C5*H*), 3.10 (dd, 1H, *J* = 2.6, 9.3 Hz, C3*H*), 3.17 (t, 1H, *J* = 8.4 Hz, C6′*H*H), 3.35 (dd, 1H, *J* = 5.5, 8.4 Hz, C6′*H*H), 3.65 (dd, 1H, *J* = 6.6, 11.2 Hz, C6*H*H), 3.70 (s, 3H, O*C*H$_3$), 3.73 (4H, C2*H*, O*C*H$_3$), 3.77–3.81 (11H, C6*H*H, C4*H*, OCH$_3$ × 3), 3.93 (2H, C2′*H*, C3′*H*), 4.09 (1H, C4′*H*), 4.32–4.38 (4H, C1*H*, ArC*H*HO × 3), 4.47 (br dd, 1H, *J* = 5.5, 8.4 Hz, C5′*H*), 4.48, 4.52 (each d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.59, 4.64 (each s, 2H, Ar*C*H$_2$O), 4.76 (d, 1H, *J* = 10.6 Hz, ArC*H*HO), 4.96 (d, 1H, *J* = 2.5 Hz, C1′*H*), 6.66 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.71 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.73 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.85 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.89 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.96 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.05 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.08–7.21 (24H, *aromatic protons*), 7.26–7.30 (4H, *aromatic protons*), 7.35–7.38 (11H, *aromatic protons*), 7.62 (br dd, 2H, *J* = 1.1, 8.4 Hz, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.14, 55.16, 55.23, 55.24, 55.27 (each O*C*H$_3$), 62.48 (*C*6′), 63.28 (*C*6), 70.21 (*C*5′), 71.53, 72.18, 72.64 (each Ar*C*H$_2$O), 73.71 (*C*4), 74.09, 75.03 (each Ar*C*H$_2$O), 75.14 (*C*4′), 75.81 (*C*2′), 76.61 (*C*2), 77.59 (*C*5), 78.97 (*C*3′), 81.10 (*C*3), 86.60 (*C*Ph$_3$), 87.24 (*C*1), 87.28 (*C*Ph$_3$), 98.91 (*C*1′), 113.36, 113.51, 113.61, 113.69, 113.71, 126.54, 126.96, 127.00, 127.76, 127.85, 128.58, 128.77, 128.82, 128.85, 129.30, 129.38, 129.54, 129.82, 130.17, 130.60, 130.79, 130.95, 131.13, 131.15, 134.73, 143.82, 144.17, 158.85, 158.87, 158.94, 158.95, 159.20 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1541.6208 (13, calcd for $C_{96}H_{94}O_{15}SNa$ $[M+Na]^+$: 1541.6211), 1536.6622 (90, calcd for $C_{96}H_{98}NO_{15}S$ $[M+NH_4]^+$: 1536.6657).

3.8. 2,3,4-Tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-2,3-di-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethy-D-galactitol (10)

A solution of **9** (1.50 g, 0.99 mmol) in a mixture of acetone (100 mL) and H_2O (10 mL) was stirred with NBS (445 mg 2.50 mmol) at 0 °C for 15 min. After 10% aq $Na_2S_2O_3$ (5.0 mL) was added, the resulting mixture was neutralized by the addition of satd aq $NaHCO_3$ (15 mL). Acetone was removed in vacuo, and the resulting aqueous solution was extracted with EtOAc (100 mL × 3). The combined organic layer was washed with H_2O (100 mL), dried over $MgSO_4$, and then concentrated in vacuo. The residue was passed through a silica gel pad to give a residue that was dissolved in a mixture of EtOH (15 mL) and CH_2Cl_2 (15 mL). To the solution, sodium borohydride (113 mg, 2.99 mmol) was added at 0 °C, and the mixture was stirred for 30 min. The ice bath was removed, and the mixture was further stirred at room temperature for 12 h. Aqueous 1.0 M HCl (2.0 mL) was added in order to decompose the excess hydride. After ethanol was removed in vacuo, the resulting aqueous mixture was extracted with EtOAc (100 mL × 3). The combined organic layer was washed with H_2O (100 mL) and brine (100 mL) successively, dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue with silica gel column chromatography (28:72 EtOAc–hexane) gave **10** (1.30 g, 92%) as an oil: $[\alpha]_D^{25}$ +25.7 (*c* 1.35, $CHCl_3$); IR (film) 3465, 2935, 1610, 1510, 1450, 1250, 1175, 1080, 1035, 820, 730, 705 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.16 (dd, 1H, *J* = 5.0, 8.0 Hz, C1O*H*), 2.98 (dd, 1H, *J* = 3.7, 9.8 Hz, C6*H*H), 3.04 (t, 1H, *J* = 8.5 Hz, C6′*H*H), 3.23 (dd, 1H, *J* = 5.3, 8.5 Hz, C6′*H*H), 3.35 (dd, 1H, *J* = 4.3, 9.8 Hz, C6*H*H), 3.42 (dd, 1H, *J* = 5.3, 9.8 Hz, C2*H*), 3.57 (dd, 1H, *J* = 2.5, 5.3 Hz, C3*H*), 3.67–3.72 (8H, C1*H*$_2$, OCH$_3$ × 2), 3.773, 3.775, 3.785 (each s, 3H, O*C*H$_3$), 3.89 (dd, 1H, *J* = 2.3, 10.2 Hz, C3′*H*), 3.93 (dd, 1H, *J* = 3.4, 10.2 Hz, C2′*H*), 4.06 (2H, C4′*H*, ArC*H*HO), 4.13 (dddd, 1H, *J* = 3.4, 3.7, 4.3, 6.5 Hz, C5*H*), 4.20 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.21 (br dd, 1H, *J* = 5.3, 8.5 Hz, C5′*H*), 4.25 (dd, 1H, *J* = 2.5, 6.5 Hz, C4*H*), 4.31 (d, 1H, *J* = 3.4 Hz, C5O*H*), 4.32 (d, 1H, *J* = 10.5 Hz, ArC*H*HO), 4.36, 4.48 (each d, 1H, *J* = 12.1 Hz, ArC*H*HO), 4.52 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.63, 4.67 (each d, 1H, *J* = 11.4 Hz, ArC*H*HO), 4.69 (d, 1H, *J* = 10.5 Hz, ArC*H*HO), 4.72 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.93 (dd, 1H, *J* = 3.4 Hz, C1′*H*), 6.65 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.71 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.78 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.79 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.88 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.97 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.99 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.02 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.14–7.26 (20H, *aromatic protons*), 7.30 (8H, *aromatic protons*), 7.41 (6H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.14 (OCH$_3$ × 2), 55.23 (OCH$_3$ × 3), 61.68 (*C*6′), 61.74 (*C*1), 64.50 (*C*6), 70.19 (*C*5), 70.42 (*C*5′), 71.72, 72.22, 72.28, 73.94, 74.26 (each Ar*C*H$_2$O), 74.84 (*C*4′), 75.55 (*C*2′), 77.21 (*C*3), 79.17 (*C*3′), 80.20 (*C*2), 80.77 (*C*4), 86.39, 86.70 (each *C*Ph$_3$), 101.67 (*C*1′), 113.35, 113.61, 113.67, 113.74 (×2), 126.91, 126.98, 127.79, 127.81, 128.63, 128.64, 129.02, 129.19 (×2), 129.45, 129.79, 130.21, 130.24, 130.33, 130.82, 130.98, 143.71, 144.06, 158.88, 158.97, 159.07, 159.08, 159.28 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1541.6210 (100, calcd for $C_{90}H_{92}O_{16}Na$ $[M+Na]^+$: 1541.6283), 1446.6669 (82, calcd for $C_{90}H_{96}NO_{16}S$ $[M+NH_4]^+$: 1446.6729).

3.9. (3*S*,4*S*,5*S*)-6-(*tert*-Butyldimethylsilyloxy)-4,5-di-(4-methoxyphenylmethoxy)-2-triphenylmethoxy-hex-1-en-3-yl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranoside (11)

A solution of **10** (1.49 g, 1.0 mmol) in DMF (10 mL) was stirred with imidazole (212 mg, 3.12 mmol) and *tert*-butyldimethylchlorosilane (235 mg, 1.56 mmol) at room temperature for 30 min. The mixture was poured into H_2O (70 mL), and the aqueous layer was extracted with EtOAc (100 mL × 3). The combined organic layer was washed with H_2O (100 mL) and brine (100 mL) successively, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (20:80 EtOAc–hexane)

gave 2,3,4-*O*-tri-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-β-D-galactopyranosyl-(1→4)-1-*O*-(*tert*-butyldimethylsilyl)-2,3-di-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-D-galactitol (1.57 g, 98%) as an oil: $[\alpha]_D^{25}$ +24.5 (*c* 1.15, $CHCl_3$); IR (film) 3465, 2930, 1610, 1510, 1250, 1080, 1035, 830, 705 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ −0.07, −0.05 (each 3H, s, SiC*H*$_3$), 0.81 (9H, s, SiC(C*H*$_3$)$_3$), 2.93 (dd, 1H, *J* = 3.3, 10.0 Hz, C6′*H*H), 3.02 (t, 1H, *J* = 8.7 Hz, C6*H*H), 3.21 (dd, 1H, *J* = 5.0, 8.7 Hz, C6*H*H), 3.36 (dd, 1H, *J* = 6.0, 10.0 Hz, C6′HH), 3.49 (2H, C2′*H*, C3′*H*), 3.69, 3.71 (each s, 3H, OC*H*$_3$), 3.76–3.79 (10H, C1′*H*H, OC*H*$_3$ × 3), 3.87–3.91 (3H, C1′*H*H, C2*H*, C3*H*), 4.11 (2H, C4*H*, C5′*H*), 4.17, 4.24 (each d, 1H, *J* = 11.1 Hz, ArC*H*HO), 4.25–4.31 (3H, C4′*H*, C5*H*, ArC*H*HO), 4.35 (d, 1H, *J* = 12.3 Hz, ArC*H*HO), 4.41 (d, 1H, *J* = 3.3 Hz, C5′O*H*), 4.44 (d, 1H, *J* = 12.3 Hz, ArC*H*HO), 4.52 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.60, 4.63 (each d, 1H, *J* = 11.4 Hz, ArC*H*HO), 4.67 (d, 1H, *J* = 10.4 Hz, ArC*H*HO), 4.71 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.90 (d, 1H, *J* = 2.8 Hz, C1*H*), 6.62 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.71 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.75 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.76 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.88 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.96 (4H, *aromatic protons*), 7.02 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.14–7.32 (28H, *aromatic protons*), 7.42 (6H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.27 (SiCH$_3$ × 2), 18.25 (Si*C*), 25.98 (SiC(*C*H$_3$)$_3$), 55.12 (OCH$_3$ × 2), 55.21 (OCH$_3$), 55.22 (OCH$_3$ × 2), 61.47 (*C*6), 64.09 (*C*1′), 64.46 (*C*6′), 70.25 (*C*5), 70.38 (*C*5′), 71.59, 72.10, 72.89, 73.86, 74.27 (each ArCH$_2$O), 74.75 (*C*4), 75.57 (*C*2), 76.87 (*C*3′), 79.44 (*C*3), 81.18 (*C*4′), 81.62 (*C*2′), 86.26, 86.66 (each *C*Ph$_3$), 101.88 (*C*1), 113.32, 113.41, 113.49, 113.71, 113.72, 126.83, 126.94, 127.76, 127.79, 128.61, 128.67, 128.76, 128.99, 129.01, 129.42, 129.85, 130.25, 130.57, 130.92, 131.04, 131.06, 143.75, 144.24, 158.75, 158.77, 158.84, 159.00, 159.25 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1565.7178 (41, calcd for $C_{96}H_{106}O_{16}SiNa$ $[M+Na]^+$: 1565.7148).

A solution of the product thus obtained (1.24 g, 803 μmol) in a mixture of DMSO (30 mL, 418 mmol) and Ac_2O (15 mL, 160 mmol) was stirred at room temperature for 10 h. The mixture was poured into H_2O (300 mL), and the aqueous layer was extracted with EtOAc (150 mL × 3). The organic layers were washed with H_2O (100 mL) and brine (100 mL) successively, combined, dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography (18:82 EtOAc–hexane) of the residue afforded (3*S*,4*S*,5*S*)-6-(*tert*-butyldimethylsilyloxy)-4,5-di-(4-methoxyphenylmethoxy)-1-triphenylmethoxy-2-hexanon-3-yl 2,3,5-*O*-tri-(4-methoxyphenylmethyl)-6-*O*-triphenyl methyl-α-D-galactopyranoside (1.23 g, 99%) as an oil: $[\alpha]_D^{25}$ +21.2 (*c* 1.78, $CHCl_3$); IR (film) 2930, 1730, 1610, 1510, 1250, 1090, 1035, 830, 705 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ −0.11, −0.09 (each 3H, s, SiC*H*$_3$), 0.80 (9H, s, SiC(C*H*$_3$)$_3$), 2.94 (t, 1H, *J* = 7.8 Hz, C6*H*H), 3.27 (dd, 1H, *J* = 5.8, 7.8 Hz, C6*H*H), 3.59 (1H, C5′*H*), 3.65 (dd, 1H, *J* = 2.8, 10.2 Hz, C3*H*), 3.73–3.78 (18H, C6′*H*$_2$, C2*H*, OC*H*$_3$ × 5), 3.81 (br d, 1H, *J* = 2.8 Hz, C4*H*), 3.86 (dd, 1H, *J* = 3.4, 5.8 Hz, C4′*H*), 3.97 (dd, 1H, *J* = 5.8, 7.8 Hz, C5*H*), 4.19 (d, 1H, *J* = 18.2 Hz, C1′*H*H), 4.24 (d, 1H, *J* = 10.7 Hz, ArC*H*HO), 4.25 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.39 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.40 (s, 2H, ArC*H*$_2$O), 4.41 (d, 1H, *J* = 18.2 Hz, C1′*H*H), 4.44, 4.49 (each d, 1H, *J* = 11.6 Hz, ArC*H*HO), 4.50 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.61 (d, 1H, *J* = 3.2 Hz, C1*H*), 4.62 (d, 1H, *J* = 10.7 Hz, ArC*H*HO), 4.65 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 6.67 (4H, *aromatic protons*), 6.74 (4H, *aromatic protons*), 6.88 (4H, *aromatic protons*), 6.96 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.06 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.13–7.26 (22H, *aromatic protons*), 7.31 (6H, *aromatic protons*), 7.42 (6H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.40, −5.38 (each SiCH$_3$), 18.17 (Si*C*), 25.94 (SiC(*C*H$_3$)$_3$), 55.14, 55.15 (each OCH$_3$), 55.17 (OCH$_3$ × 2), 55.21 (OCH$_3$), 62.35 (*C*6), 63.33 (*C*6′), 69.98 (*C*1′), 70.52 (*C*5), 71.92, 72.78, 72.95, 73.27, 74.10 (each ArCH$_2$O), 74.74 (*C*2), 75.17 (*C*4), 78.69 (*C*3), 80.08 (*C*4′), 80.69 (*C*5′), 82.01 (*C*3′), 86.61, 86.89 (each *C*Ph$_3$), 98.61 (*C*1), 113.33, 113.46, 113.52, 113.62, 113.67, 126.96, 126.98, 127.80, 127.82, 128.61, 128.66, 128.79, 129.43, 129.49, 129.60, 129.69, 130.31, 130.49, 130.77, 130.86, 131.14, 143.70, 143.77, 158.87, 158.88, 158.90, 158.97, 158.98 (*aromatic carbons*), 205.74 (*C*2′); ESIMS (%, rel. int.) *m*/*z*: 1563.7013 (55, calcd for $C_{96}H_{104}O_{16}SiNa$ $[M+Na]^+$: 1563.6991), 1558.7428 (91, calcd for $C_{96}H_{108}NO_{16}Si$ $[M+NH_4]^+$: 1558.7437).

A solution of the product (2.00 g, 1.30 mmol) in a mixture of toluene (30 mL) and pyridine (0.5 mL) was stirred with the second-generation Tebbe reagent[17] (0.5 M in toluene, 7.8 mL, 3.90 mmol) at −40 °C for 15 min. The ice bath was removed, and the mixture was further stirred at ambient temperature for 1 h. After 1.0 M aq NaOH (2.0 mL) was added to quench the reaction at 0 °C, the mixture was filtered through Celite, and the filtrate was concentrated in vacuo. Purification of the residue with silica gel column chromatography (18:82 EtOAc–hexane) gave **11** (1.30 g, 65%) as an oil. $[\alpha]_D^{24}$ +45.3 (*c* 1.00, $CHCl_3$); IR (film) 2925, 1610, 1510, 1250, 1090, 1035, 830, 705 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ −0.21, −0.20 (each 3H, s, SiC*H*$_3$), 0.71 (9H, s, SiC(C*H*$_3$)$_3$), 3.07 (dd, 1H, *J* = 7.0, 8.7 Hz, C6*H*H), 3.38 (dd, 1H, *J* = 6.1, 8.7 Hz, C6*H*H), 3.39–3.45 (3H, C6′*H*$_2$, C5′*H*), 3.48 (t, 1H, *J* = 3.8 Hz, C4′*H*), 3.71 (s, 3H, OC*H*$_3$), 3.73–3.77 (14H, C2′*H*$_2$, OC*H*$_3$ × 4), 3.90 (2H, C3*H*, C4*H*), 3.95 (dd, 1H, *J* = 3.4, 10.5 Hz, C2*H*), 4.18 (br dd, 1H, *J* = 6.1, 7.0 Hz, C5*H*), 4.30 (d, 1H, *J* = 12.0 Hz, ArC*H*HO), 4.31 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.41–4.51 (5H, ArC*H*HO × 5), 4.54 (d, 1H, *J* = 11.5 Hz, ArC*H*HO), 4.56 (d, 1H, *J* = 3.8 Hz, C3′*H*), 4.66 (d, 1H, *J* = 11.5 Hz, ArC*H*HO), 4.72 (d, 1H, *J* = 10.8 Hz, ArC*H*HO), 5.00 (d, 1H, *J* = 3.4 Hz, C1*H*), 5.50, 5.71 (each br s, 1H, C1′*H*), 6.64 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.67 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.69 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.78 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.80 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.95 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.97 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.07 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.14–7.23 (22H, *aromatic protons*), 7.35–7.38 (12H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.50, −5.40 (each SiCH$_3$), 18.04 (Si*C*), 25.84 (SiC(*C*H$_3$)$_3$), 55.10, 55.16, 55.17, 55.19, 55.21 (each OCH$_3$), 62.86 (*C*6), 63.36 (*C*6′), 64.51 (C2′*C*H$_2$), 70.12 (*C*5), 72.49, 72.53, 72.57, 72.87, 74.03 (each ArCH$_2$O), 75.44 (*C*4), 75.86 (*C*2), 76.68 (*C*3′), 77.68 (*C*4′), 78.57 (*C*3), 78.71 (*C*5′), 86.58, 86.84 (each *C*Ph$_3$), 94.31 (*C*1), 113.35 (×2), 113.39, 113.52, 113.60 (*aromatic carbons*), 115.10 (*C*1′), 126.88, 126.91, 127.76 (×2), 128.59, 128.73, 128.80, 129.41, 129.48, 129.54, 129.79, 130.67, 130.91, 131.00, 131.18, 131.47 (*aromatic carbons*), 143.23 (*C*2′), 143.83, 144.25, 158.77, 158.79, 158.83, 158.88, 158.90 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1561.7184 (43, calcd for $C_{97}H_{106}O_{15}SiNa$ $[M+Na]^+$: 1561.7199), 1556.7620 (88, calcd for $C_{97}H_{110}NO_{15}Si$ $[M+NH_4]^+$: 1556.7645).

3.10. (3*RS*,4*R*,5*S*,6*S*)-4,5-Di-(4-methoxyphenylmethoxy)-3-hydroxy-7-(triphenylmethoxymethyl)octa-1,7-dien-6-yl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranoside (12)

A solution of **11** (475 mg, 0.31 mmol) in THF (6.0 mL) was stirred with tetrabutylammonium fluoride (1.0 M in THF, 0.47 mL) at room temperature for 2 h. The mixture was poured into H_2O (50 mL), and the aqueous layer was extracted with EtOAc (50 mL × 3). The combined organic layer was washed with brine (50 mL), dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue with silica gel column chromatography (26:74 EtOAc–hexane) gave the corresponding alcohol (422 mg, 97%) as an oil: $[\alpha]_D^{24}$ +46.5 (*c* 1.00, $CHCl_3$); IR (film) 3500, 2930, 1610, 1510, 1250, 1090, 1035, 820, 705 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 1.85 (dd, 1H, *J* = 4.8, 7.0 Hz, C6′O*H*), 2.99 (dd, 1H, *J* = 6.2, 9.0 Hz, C6*H*H), 3.35–3.44 (3H, C6*H*H, C5′*H*, C6′*H*H), 3.51 (ddd, 1H, *J* = 3.7, 7.0, 11.3 Hz, C6′*H*H), 3.59 (dd, 1H, *J* = 4.2, 6.6 Hz, C4′*H*), 3.736 (s,

3H, OCH_3), 3.741 (s, 6H, OCH_3 × 2), 3.77, 3.78 (each s, 3H, OCH_3), 3.78–3.83 (4H, C3*H*, C4*H*, C2′CH_2), 3.93 (dd, 1H, *J* = 3.6, 9.7 Hz, C2*H*), 4.00 (br d, 1H, *J* = 6.3 Hz, C5*H*), 4.26 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.33 (d, 1H, *J* = 11.0 Hz, ArC*H*HO), 4.37 (d, 1H, *J* = 11.0 Hz, ArC*H*HO), 4.40 (d, 1H, *J* = 4.2 Hz, C3′*H*), 4.42–4.46 (each d, 1H, *J* = 11.6 Hz, ArC*H*HO), 4.50 (d, 1H, *J* = 11.0 Hz, ArC*H*HO), 4.53 (d, 1H, *J* = 11.6 Hz, ArC*H*HO), 4.65 (d, 1H, *J* = 11.6 Hz, ArC*H*HO), 4.70 (d, 1H, *J* = 11.0 Hz, ArC*H*HO), 5.00 (d, 1H, *J* = 3.6 Hz, C1*H*), 5.47 (br s, 1H, C1′*H*H), 5.81 (br d, 1H, *J* = 1.7 Hz, C1′*H*H), 6.65 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.68 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.74 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.77 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.78 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.94 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.02 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.08 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.12 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.14–7.21 (22H, *aromatic protons*), 7.34–7.37 (10H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.16 (OCH_3), 55.19 (OCH_3 × 4), 62.59 (*C*6′), 63.26 (*C*6), 64.25 (C2′CH_2), 70.47 (*C*5), 72.45, 72.55, 73.07, 73.89, 73.95 (each ArCH_2O), 75.31 (*C*4), 75.59 (*C*2), 77.10 (*C*3′), 78.29 (*C*3), 79.32 (*C*5′), 80.22 (*C*4′), 86.65, 86.89 (each *C*Ph$_3$), 93.96 (*C*1), 113.39, 113.49, 113.55, 113.61, 113.67 (*aromatic carbons*), 115.85 (*C*1′), 126.91, 126.96, 127.76, 127.78, 128.56, 128.68, 128.98, 129.38, 129.49, 129.59, 129.77, 130.64, 130.76, 130.77, 130.80, 130.98 (*aromatic carbons*), 142.58 (*C*2′), 143.82, 144.17, 158.89, 158.92, 158.94 (×2), 159.06 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1447.6312 (62, calcd for $C_{91}H_{92}O_{15}Na$ [M+Na]$^+$: 1447.6334), 1442.6766 (98, calcd for $C_{91}H_{96}NO_{15}$ [M+NH$_4$]$^+$: 1442.6780).

Oxalyl chloride (164 mg, 1.29 mmol) was added to a solution of dimethyl sulfoxide (202 mg, 2.59 mmol) in CH_2Cl_2 (3.0 mL) at −78 °C, and the mixture was stirred for 10 min. To the mixture, a solution of the product (610 mg, 428 μmol) in CH_2Cl_2 (3.0 mL) was added, and the resulting mixture was stirred at the same temperature for 40 min. After Et_3N (392 mg, 3.87 mmol) was added, the cooling bath was removed. The mixture was further stirred at room temperature for additional 10 min. The mixture was poured into H_2O (50 mL), and the aqueous layer was extracted with EtOAc (50 mL × 3). The combined organic layer was washed with brine (50 mL), dried over $MgSO_4$, and then concentrated in vacuo to give the crude aldehyde, which was immediately dissolved in THF (10 mL). Vinylmagnesium bromide (1.0 M in THF, 0.86 mL) was added to the THF solution at −15 °C, and the mixture was stirred for 5 min, then at 0 °C for an additional 10 min. It was then poured into satd aq NH_4Cl (50 mL), and the aqueous layer was extracted with EtOAc (50 mL × 3). The combined organic layer was washed with brine (50 mL), dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue with silica gel column chromatography (26:74 EtOAc–hexane) gave **12** as a 7:10 isomeric mixture (506 mg, 81%): $[\alpha]_D^{24}$ +42.3 (*c* 1.46, $CHCl_3$); IR (film) 3485, 2930, 1610, 1510, 1250, 1090, 1035, 820, 705 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$, assignments for signals of the major isomer and only some of minor isomer are described) δ 2.26 (d, 1H × 0.4, *J* = 6.8 Hz, C6′O*H* ((*R*)-isomer)), 2.43 (d, 1H × 0.6, *J* = 7.4 Hz, C6′O*H* ((*S*)-isomer)), 2.95 (dd, 1H × 0.6, *J* = 6.0, 9.0 Hz, C6*H*H ((*S*)-isomer)), 3.03 (dd, 1H × 0.4, *J* = 6.3, 9.0 Hz, C6*H*H ((*R*)-isomer)), 3.24 (dd, 1H × 0.4, *J* = 3.5, 6.7 Hz, C5′*H* ((*R*)-isomer)), 3.37 (dd, 1H × 0.6, *J* = 6.6, 9.0 Hz, C6*H*H ((*S*)-isomer)), 3.42 (1H, C6*H*H ((*R*)-isomer), C5′*H* ((*S*)-isomer)), 3.60 (t, 1H × 0.6, *J* = 5.5 Hz, C4′*H* ((*S*)-isomer)), 3.67–3.82 (19H, C2′CH_2, C4′*H* ((*R*)-isomer), C4*H*, C3*H* ((*S*)-isomer), OCH_3 × 5), 3.85 (dd, 1H × 0.4, *J* = 2.6, 10.1 Hz, C3*H* ((*R*)-isomer)), 3.93–4.09 (3H, C2*H*, C6′*H*, C5*H*), 4.26–4.72 (11H, ArC*H*HO × 10, C3′*H*), 4.91 (br d, 1H × 0.6, *J* = 10.5 Hz, C8′*H* ((*S*)-isomer)), 4.93 (br d, 1H × 0.4, *J* = 10.6 Hz, C8′*H* ((*R*)-isomer)), 4.95 (br d, 1H × 0.4, *J* = 17.1 Hz, C8′*H* ((*R*)-isomer)), 5.03 (d, 1H × 0.6, *J* = 3.7 Hz, C1*H* ((*S*)-isomer)), 5.05 (d, 1H × 0.4, *J* = 3.6 Hz, C1*H* ((*R*)-isomer)), 5.09 (br d, 1H × 0.6, *J* = 17.2 Hz, C8′*H* ((*S*)-isomer)), 5.50 (br s, 1H × 0.4, C1′*H* ((*R*)-isomer)), 5.53 (br s, 1H × 0.6, C1′*H* ((*S*)-isomer)), 5.57 (ddd, 1H × 0.4, *J* = 5.8, 10.6, 17.1 Hz, C7′*H* ((*R*)-isomer)), 5.72 (ddd, 1H × 0.6, *J* = 6.0, 10.5, 17.2 Hz, C7′*H* ((*S*)-isomer)), 5.83 (br d, 1H × 0.4, *J* = 1.7 Hz, C1′*H* ((*R*)-isomer)), 5.86 (br d, 1H × 0.6, *J* = 1.6 Hz, C1′*H* ((*S*)-isomer)), 6.63–7.38 (50H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.14, 55.16 (each OCH_3), 55.19 (OCH_3 × 3), 63.06 (*C*6 ((*R*)-isomer)), 63.33 (*C*6 ((*S*)-isomer)), 64.10 (C2′CH_2 ((*R*)-isomer)), 64.26 (C2′CH_2 ((*S*)-isomer)), 70.37 (*C*5 ((*R*)-isomer)), 70.58 (*C*5 ((*S*)-isomer)), 72.43, 72.47, 72.51 (each ArCH_2O), 72.55 (*C*6′ ((*R*)-isomer), ArCH_2O), 73.15 (*C*6′ ((*S*)-isomer)), 73.49, 73.63, 73.79, 73.84, 73.97, 74.48 (each ArCH_2O), 75.05 (*C*4 ((*S*)-isomer)), 75.32 (*C*4 ((*R*)-isomer)), 75.60 (*C*2 ((*S*)-isomer)), 75.68 (*C*2 ((*R*)-isomer)), 76.88 (*C*3′ ((*R*)-isomer)), 77.39 (*C*3′ ((*S*)-isomer)), 78.36 (*C*3 ((*R*)-isomer)), 78.62 (*C*3 ((*S*)-isomer)), 79.32 (*C*4′ ((*R*)-isomer)), 79.37 (*C*4′ ((*S*)-isomer)), 80.31 (*C*5′ ((*R*)-isomer)), 80.36 (*C*5′ ((*S*)-isomer)), 86.58, 86.66, 86.83, 86.92 (each *C*Ph$_3$), 93.86 (*C*1 ((*R*)-isomer)), 94.02 (*C*1 ((*S*)-isomer)), 113.37, 113.39, 113.43, 113.49, 113.53 (×2), 113.54, 113.56, 113.60, 113.61 (*aromatic carbons*), 115.70 (*C*1′ ((*S*)-isomer)), 115.73 (*C*1′ ((*R*)-isomer)), 115.89 (*C*8′ ((*R*)-isomer)), 116.57 (*C*8′ ((*S*)-isomer)), 126.92, 127.78 (×2), 128.54, 128.66, 128.70, 128.90, 128.92, 129.32, 129.35, 129.49, 129.54, 129.55, 129.74, 129.88, 129.99, 130.43, 130.72, 130.74, 130.76 (×3), 130.81, 130.83, 130.95, 131.00 (*aromatic carbons*), 137.17 (*C*7′ ((*S*)-isomer)), 138.34 (*C*7′ ((*R*)-isomer)), 142.60 (*C*2′ ((*S*)-isomer)), 142.76 (*C*2′ ((*R*)-isomer)), 143.80 (×2), 144.14, 144.16, 158.86 (×2), 158.88, 158.89, 158.91 (×2),158.92, 158.97, 158.98, 159.06 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1473.6505 (62, calcd for $C_{93}H_{94}O_{15}Na$ [M+Na]$^+$: 1473.6490), 1468.6932 (99, calcd for $C_{93}H_{98}NO_{15}$ [M+NH$_4$]$^+$: 1468.6936).

3.11. 2,3,4-*O*-Tri-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-2,3-di-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-$\Delta^{5,5a}$-carba-D-galactopyranose (13α) and its C1 β-isomer (13β)

A solution of **12** (486 mg, 0.335 mmol) in toluene (25.0 mL) was stirred in the presence of Grubbs's second-generation catalyst[26] (11.8 mg, 13.9 μmol) at 100 °C. After 10 min, the mixture was concentrated in vacuo. Purification of the residue by silica gel chromatography (28:72 EtOAc–hexane) gave a 10:7 mixture of **13α** and **13β** as an oil. These were separated by medium-pressure silica gel column chromatography (6:94 EtOAc–benzene) to provide **13α** (233 mg, 49%) and **13β** (162 mg, 34%).

3.11.1. Physicochemical and spectral data for 13α

$[\alpha]_D^{25}$ +44.6 (*c* 1.34, $CHCl_3$); IR (film) 3500, 2930, 1610, 1510, 1250, 1090, 1035, 820, 705 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.32 (d, 1H, *J* = 5.0 Hz, C1O*H*), 3.18 (t, 1H, *J* = 8.3 Hz, C6′*H*H), 3.32 (dd, 1H, *J* = 5.6, 8.3 Hz, C6′*H*H), 3.68 (4H, C3*H*, OCH_3), 3.74, 3.76 (each s, 3H, OCH_3), 3.78 (s, 6H, OCH_3 × 2), 3.79 (1H, C3′*H*), 3.86 (dd, 1H, *J* = 3.4, 10.1 Hz, C2′*H*), 3.91 (3H, C2*H*, C6H_2), 4.05 (br s, 1H, C4′*H*), 4.23 (d, 1H, *J* = 2.9 Hz, C4*H*), 4.28 (1H, C1*H*), 4.34 (d, 1H, *J* = 10.6 Hz, ArC*H*HO), 4.35 (1H, C5′*H*), 4.36 (s, 2H, ArCH_2O), 4.39 (d, 1H, *J* = 12.6 Hz, ArC*H*HO), 4.50 (2H, ArC*H*HO × 2), 4.55, 4.59 (each d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.61 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.76 (d, 1H, *J* = 10.6 Hz, ArC*H*HO), 4.88 (d, 1H, *J* = 3.4 Hz, C1′*H*), 5.71 (br d, 1H, *J* = 3.9 Hz, C5a*H*), 6.68–6.74 (6H, *aromatic protons*), 6.82 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.95 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.06 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.12–7.19 (24H, *aromatic protons*), 7.24 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.33–7.36 (10H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.15, 55.17 (each OCH_3), 55.21 (OCH_3 × 2), 55.22 (OCH_3), 62.28 (*C*6′), 64.65 (*C*6), 65.78 (*C*1), 70.29 (*C*5′), 71.95, 72.35, 72.46, 72.62 (each ArCH_2O), 73.55 (*C*4), 74.03 (ArCH_2O), 75.19 (*C*4′), 75.32 (*C*2 or *C*3), 75.36 (*C*2 or *C*3), 75.55 (*C*2′), 78.90 (*C*3′), 86.66, 87.06 (each *C*Ph$_3$), 98.70 (*C*1′), 113.35,

113.58, 113.62 (×2), 113.75 (*aromatic carbons*), 124.63 (*C*5a), 126.90, 126.98, 127.75, 127.80, 128.61, 128.72, 128.84, 129.02, 129.37, 129.41, 129.49, 130.33, 130.69, 130.80, 131.04, 131.12 (*aromatic carbons*), 137.55 (*C*5), 143.71, 144.23, 157.92, 158.85, 158.93, 158.94, 159.23 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1445.6113 (23, calcd for $C_{91}H_{90}O_{15}Na$ $[M+Na]^+$: 1445.6177), 1440.6564 (98, calcd for $C_{91}H_{94}NO_{15}$ $[M+NH_4]^+$: 1440.6623).

3.11.2. Physicochemical and spectral data for 13β

$[\alpha]_D^{24}$ +32.5 (*c* 0.72, $CHCl_3$); IR (film) 3465, 2930, 1610, 1510, 1250, 1090, 1035, 820, 720 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 3.05 (dd, 1H, *J* = 6.9, 8.7 Hz, C6′*H*H), 3.36 (2H, C6′*H*H, C3*H*), 3.43 (br, 1H, C1O*H*), 3.68, 3.70 (each s, 3H, OCH_3), 3.75 (2H, C6H_2), 3.77, 3.782, 3.784 (each s, 3H, OCH_3), 3.85 (dd, 1H, *J* = 3.6, 10.0 Hz, C2′*H*), 3.93 (dd, 1H, *J* = 2.6, 10.0 Hz, C3′*H*), 3.96 (br d, 1H, *J* = 2.6 Hz, C4′*H*), 3.98 (dd, 1H, *J* = 3.5, 8.2 Hz, C2*H*), 4.06 (1H, C1*H*), 4.29–4.34 (3H, C4*H*, C5′*H*, ArC*H*HO), 4.41 (d, 1H, *J* = 12.4 Hz, ArC*H*HO), 4.49, 4.55 (each d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.60 (d, 1H, *J* = 12.4 Hz, ArC*H*HO), 4.62, 4.68 (each d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.72 (d, 1H, *J* = 12.0 Hz, ArC*H*HO), 4.73 (s, 2H, ArCH_2O), 4.76 (d, 1H, *J* = 3.6 Hz, C1′*H*), 5.97 (br d, 1H, *J* = 4.6 Hz, C5a*H*), 6.64 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.69 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.74 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.87 (4H, *aromatic protons*), 6.93 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.09 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.13–7.17 (20H, *aromatic protons*), 7.28 (4H, *aromatic protons*), 7.32–7.35 (12H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.10, 55.14, 55.21 (×2), 55.24 (each OCH_3), 62.53 (*C*6′), 65.42 (*C*6), 70.31 (*C*5′), 70.83 (ArCH_2O), 70.87 (*C*4), 71.19 (*C*1), 72.58, 72.80, 72.96, 74.02 (each ArCH_2O), 75.17 (*C*4′), 75.31 (*C*2′), 78.88 (*C*3′), 79.99 (*C*3), 83.13 (*C*2), 78.90 (*C*3′), 86.60, 87.05 (each *C*Ph$_3$), 96.54 (*C*1′), 113.36, 113.60, 113.66, 113.68, 113.74, 126.94, 127.05 (*aromatic carbons*), 127.74 (*C*5a, *aromatic carbon*), 127.86, 128.50, 128.71, 128.94, 129.07, 129.49, 129.52, 129.76, 130.14, 130.33, 130.80, 130.89, 130.99 (*aromatic carbons*), 138.29 (*C*5), 143.71, 143.89, 158.87, 158.92, 158.98, 159.11, 159.12 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 1445.6183 (32, calcd for $C_{91}H_{90}O_{15}Na$ $[M+Na]^+$: 1445.6177), 1440.6611 (96, calcd for $C_{91}H_{94}NO_{15}$ $[M+NH_4]^+$: 1440.6623).

3.12. Stereochemical inversion of the C1 moiety of 13α

A solution of **13α** (104 mg, 73.1 μmol) in THF (3.5 mL) was stirred with triphenylphosphine (58.0 mg, 221 μmol), *p*-nitrobenzoic acid (37.0 mg, 221 μmol), and diethyl azodicarboxylate (2.2 M solution in toluene, 86.0 μL, 221 μmol) at room temperature for 40 min. The mixture was poured into satd aq NH_4Cl (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. Purification of the residue with successive silica gel column chromatography (24:76 EtOAc–hexane) and (4:96 EtOAc–benzene) gave the corresponding *p*-nitrobenzoate with β-stereochemistry (110 mg, 96%) as an oil: $[\alpha]_D^{25}$ −13.8 (*c* 1.33, $CHCl_3$); IR (film) 2935, 1725, 1610, 1510, 1250, 1095, 1035, 820, 700 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 3.25 (2H, C6′*H*H, C3*H*), 3.40 (dd, 1H, *J* = 5.4, 8.2 Hz, C6′*H*H), 3.658, 3.663, 3.72, 3.78, 3.80 (each s, 3H, OCH_3), 3.83 (br d, 1H, *J* = 14.5 Hz, C6*H*H), 4.01 (2H, C2′*H*, C3′*H*), 4.13–4.18 (2H, C6*H*H, C2*H*), 4.19 (br s, 1H, C4′*H*), 4.24 (d, 1H, *J* = 3.3 Hz, C4*H*), 4.37 (d, 1H, *J* = 10.5 Hz, ArC*H*HO), 4.40 (d, 1H, *J* = 12.7 Hz, ArC*H*HO), 4.50 (d, 1H, *J* = 12.7 Hz, ArC*H*HO), 4.53 (1H, C5′*H*), 4.55 (s, 2H, ArCH_2O), 4.70 (d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.74 (s, 2H, ArCH_2O), 4.82 (2H, ArCH_2O × 2), 5.03 (br s, 1H, C1′*H*), 5.25 (br s, 1H, C5a*H*), 5.28 (br d, 1H, *J* = 7.7 Hz, C1*H*), 6.59 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.65 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.73 (4H, *aromatic protons*), 6.89 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.99 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.12–7.20 (26H, *aromatic protons*), 7.25–7.29 (8H, *aromatic protons*), 7.32 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.37 (4H, *aromatic protons*), 7.92 (br d, 2H, *J* = 9.0 Hz, *aromatic protons*), 8.18 (br d, 2H, *J* = 9.0 Hz, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 54.99, 55.10, 55.19, 55.21, 55.24 (each OCH_3), 62.05 (*C*6′), 65.05 (*C*6), 70.28 (*C*5′), 71.59, 72.30, 72.57 (each ArCH_2O), 72.81 (*C*4), 73.59, 74.11 (each ArCH_2O), 74.82 (*C*1), 74.95 (*C*4′), 75.60 (*C*2′), 76.23 (*C*2), 77.14 (*C*3), 79.27 (*C*3′), 86.66, 87.25 (each CPh_3), 98.91 (*C*1′), 113.39, 113.54, 113.67 (×2), 113.70 (*aromatic carbons*), 122.12 (*C*5a), 123.23, 127.02, 127.13, 127.77, 127.90, 128.45, 128.72, 128.81, 129.09, 129.35, 129.54, 129.96, 130.31, 130.48, 130.61, 130.83, 130.96, 130.99, 135.33 (*aromatic carbons*), 138.36 (*C*5), 143.70, 144.00, 150.36, 158.91, 159.01 (×2), 159.03 (×2), 164.06 (*aromatic carbons*), 203.76 (*C*=O); ESIMS (%, rel. int.) *m*/*z*: 1594.6276 (37, calcd for $C_{98}H_{93}NO_{18}Na$ $[M+Na]^+$: 1594.6290), 1589.6686 (93, calcd for $C_{98}H_{97}N_2O_{18}$ $[M+NH_4]^+$: 1589.6736).

The product was diluted with a mixture of MeOH (3.0 mL) and CH_2Cl_2 (3.0 mL) and stirred with aq 1.0 M NaOH (0.3 mL) at room temperature for 30 min. The mixture was poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (20 mL), dried over $MgSO_4$, and concentrated in vacuo. Silica gel column chromatography of the residue (30:70 EtOAc–hexane) gave **13β** (91.8 mg, 92%). The ^1H NMR spectrum and R_f value in the silica gel TLC were identical to the sample **13β** described in Section 3.11.2.

3.13. α-D-Galactopyranosyl-(1→4)-β-D-$\Delta^{5,5a}$-carba-D-galactopyranose (14β)

To a solution of **13β** (67.0 mg, 47.1 mmol) in CH_2Cl_2 (3.0 mL), 90% aq formic acid (0.2 mL) was added at 0 °C. After stirring at 0 °C for 1 h, the cooling bath was removed, and the mixture was stirred at room temperature for additional 1 h. After satd aq $NaHCO_3$ (1.0 mL) was added at 0 °C, the mixture was poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. The residue was passed through a silica gel pad to give the corresponding triol, which was dissolved in a mixture of CH_2Cl_2 (1.0 mL) and H_2O (100 μL) without purification. To the solution, 2,3-dicyano-5,6-dichlorobenzoquinone (DDQ) (60.0 mg, 0.26 mmol) was added, and the resulting suspension was stirred at room temperature for 40 h. The mixture was poured into water (10 mL), and the aqueous layer was washed with EtOAc (10 mL × 2). The aqueous solution was collected and concentrated in vacuo to give the crude product. It was then loaded onto an ODS Sep-Pak® cartridge (5.0 g) after dilution with small amount of H_2O (ca. 0.3 mL). Elution with 95:5 H_2O–MeOH and subsequent lyophilization gave **14β** (8.7 mg, 55%) as a white powder: $[\alpha]_D^{24}$ +143 (*c* 0.63, H_2O); ^1H NMR (500 MHz, D_2O) δ 3.51 (dd, 1H, *J* = 3.5, 10.6 Hz, C3*H*), 3.59, 3.60 (each s, 1H, C6′*H*H), 3.67 (dd, 1H, *J* = 7.3, 10.6 Hz, C2*H*), 3.69 (dd, 1H, *J* = 3.6, 8.5 Hz, C2′*H*), 3.73 (dd, 1H, *J* = 3.0, 8.5 Hz, C3′*H*), 3.86 (dd, 1H, *J* = 1.0, 3.0 Hz, C4′*H*), 3.97 (br d, 1H, *J* = 7.3 Hz, C1*H*), 4.04–4.10 (3H, C5′*H*, C6′H_2), 4.16 (d, 1H, *J* = 3.5 Hz, C4*H*), 4.95 (d, 1H, *J* = 3.6 Hz, C1′*H*), 5.64 (1H, C5a*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 60.84 (*C*6′), 62.78 (*C*6), 68.48 (*C*3′), 69.06 (*C*4′), 69.25 (*C*2′), 70.95 (*C*3), 71.33 (*C*5′), 72.01 (*C*1), 72.89 (*C*2), 77.09 (*C*4), 100.17 (*C*1′), 128.30 (*C*5a), 136.67 (*C*5); ESIMS (%, rel. int.) *m*/*z*: 361.1116 (100, calcd for $C_{13}H_{22}O_{10}Na$ $[M+Na]^+$: 361.1111), 339.1317 (0.8, calcd for $C_{13}H_{23}O_{10}$ $[M+H]^+$: 339.1291).

3.14. α-D-Galactopyranosyl-(1→4)-α-D-$\Delta^{5,5a}$-carba-D-galactopyranose (14α)

In a similar manner as described for the preparation of **14β** in Section 3.13, **13α** (68.0 mg, 47.8 μmol) was treated with 90% aq

HCO_2H (0.2 mL) in CH_2Cl_2 (3.0 mL). A similar work up afforded the triol (30.0 mg, 67%) as a caramel product. The product (24.0 mL, 25.6 μmol) was treated with DDQ (58.0 mg, 0.26 mmol) in a mixture of H_2O (0.2 mL), and CH_2Cl_2 (2.0 mL). A similar work up afforded **14α** (6.2 mg, 71%) as white powder. $[\alpha]_D^{24}$ +110 (*c* 0.62, H_2O); ^1H NMR (400 MHz, D_2O) δ 3.61 (d, 2H, *J* = 6.2 Hz, C6′H_2), 3.70 (dd, 1H, *J* = 3.7, 11.4 Hz, C2′*H*), 3.74 (dd, 1H, *J* = 3.0, 11.4 Hz, C3′*H*), 3.86 (dd, 1H, *J* = 1.1, 3.0 Hz, C4′*H*), 3.96 (dd, 1H, *J* = 4.1, 7.3 Hz, C2*H*), 4.036 (dt, 1H, *J* = 1.1, 6.2 Hz, C5′*H*), 4.04 (br d, 1H, *J* = 14.5 Hz, C6*H*H), 4.08 (dd, 1H, *J* = 3.8, 7.3 Hz, C3*H*), 4.11 (br d, 1H, *J* = 14.5 Hz, C6*H*H), 4.29 (br, 1H, C1*H*), 4.33 (br d, 1H, *J* = 3.8 Hz, C4*H*), 5.01 (d, 1H, *J* = 3.7 Hz, C1′*H*), 5.64 (1H, C5a*H*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 61.04 (*C*6′), 62.55 (*C*6), 65.56 (*C*1), 68.54 (*C*2′), 69.17 (*C*4′), 69.34 (*C*3′), 69.99 (*C*2), 70.15 (*C*3), 71.43 (*C*5′), 76.12 (*C*4), 100.84 (*C*1′), 125.93 (*C*5a), 137.37 (*C*5); ESIMS (%, rel. int.) *m*/*z*: 361.1112 (100, calcd for $C_{13}H_{22}O_{10}Na$ $[M+Na]^+$: 361.1111), 356.1568 (1.8, calcd for $C_{13}H_{26}NO_{10}$ $[M+NH^4]^+$: 356.1557), 339.1317 (0.6, calcd for $C_{13}H_{23}O_{10}$ $[M+H]^+$: 339.1291).

3.15. 2,3,4-Tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-2,3-di-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-1-acetylthio-α-$\Delta^{5,5a}$-carba-D-galactopyranose (15)

A solution of **13β** (91.8 mg, 64.5 μmol) in CH_2Cl_2 (3.0 mL) was stirred with methanesulfonic anhydride (45.0 mg, 258 μmol) and Et_3N (65.3 mg, 0.65 mmol) at −20 °C for 10 min. After the mixture was stirred at 0 °C for 10 min, it was poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (20 mL), dried over $MgSO_4$, and concentrated in vacuo to give the crude mesylate, which was immediately diluted with DMF (3.0 mL). Potassium thioacetate (37.0 mg, 0.32 mmol) was added to the solution at room temperature. After stirring for 5 h, the mixture was poured into H_2O (25 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was successively washed with H_2O (30 mL) and brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (26:74 EtOAc–hexane) gave **15** (93.8 mg, 98%) as an oil: $[\alpha]_D^{25}$ +71.2 (*c* 1.09, $CHCl_3$); IR (film) 2930, 1690, 1610, 1510, 1250, 1090, 1035, 820, 730, 705 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 2.36 (s, 3H, COC*H*$_3$), 3.21 (t, 1H, *J* = 8.4 Hz, C6′*H*H), 3.31 (2H, C6′*H*H, C3*H*), 3.66 (s, 3H, OC*H*$_3$), 3.73 (1H, C3′*H*), 3.74, 3.75, 3.78, 3.79 (each s, 3H, OC*H*$_3$), 3.86 (2H, C6*H*H, C2′*H*), 3.94 (br d, 1H, *J* = 13.9 Hz, C6*H*H), 4.08 (dd, 1H, *J* = 4.9, 8.9 Hz, C2*H*), 4.14 (br s, 1H, C4′*H*), 4.17 (d, 1H, *J* = 3.1 Hz, C4*H*), 4.34 (s, 2H, ArC*H*$_2$O), 4.36 (d, 1H, *J* = 10.4 Hz, ArC*H*HO), 4.39–4.41 (2H, C5′*H*, ArC*H*HO), 4.45 (d, 1H, *J* = 13.0 Hz, ArC*H*HO), 4.48 (d, 1H, *J* = 12.0 Hz, ArC*H*HO), 4.56 (s, 2H, ArC*H*$_2$O), 4.57 (d, 1H, *J* = 12.0 Hz, ArC*H*HO), 4.64 (t, 1H, *J* = 4.9 Hz, C1*H*), 4.79 (d, 1H, *J* = 10.4 Hz, ArC*H*HO), 4.89 (d, 1H, *J* = 3.5 Hz, C1′*H*), 5.45 (br d, 1H, *J* = 4.9 Hz, C5a*H*), 6.68–6.72 (6H, *aromatic protons*), 6.84 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.96 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.05 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.14–7.37 (36H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) δ 30.66 (*C*H$_3$CO), 44.49 (*C*1), 55.14, 55.16 (each OCH$_3$), 55.21 (OCH$_3$ × 3), 61.92 (*C*6′), 64.59 (*C*6), 70.08 (*C*5′), 71.90, 72.19, 72.30, 72.39 (each ArCH$_2$O), 73.18 (*C*2), 74.04 (ArCH$_2$O), 74.40 (*C*4), 75.06 (*C*4′), 75.27 (*C*2′), 76.44 (*C*3), 79.04 (*C*3′), 86.66, 87.19 (each *C*Ph$_3$), 99.26 (*C*1′), 113.33, 113.56, 113.58, 113.60 (×2) (*aromatic carbons*), 122.86 (*C*5a), 126.969, 126.974, 127.76, 127.77, 128.52, 128.72, 128.77, 129.01, 129.17, 129.46, 129.48, 130.49, 130.60, 130.91, 131.14, 131.16 (*aromatic carbons*), 136.89 (*C*5), 143.75, 144.20, 158.82, 158.85, 158.88, 158.92, 158.99 (*aromatic carbons*), 195.22 (*C*=O); ESIMS (%, rel. int.) *m*/*z*: 1503.6074 (30, calcd for $C_{93}H_{92}O_{15}SNa$ $[M+Na]^+$: 1503.6055), 1498.6508 (98, calcd for $C_{93}H_{96}NO_{15}S$ $[M+NH_4]^+$: 1498.6501).

3.16. 2,3,4-Tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-2,3-di-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-1-thio-α-$\Delta^{5,5a}$-carba-D-galactopyranose (16)

A solution of **15** (93.8 mg, 63.3 μmol) in DMF (3.0 mL) was stirred with hydrazine acetate (12.0 mg, 261 μmol) at 0 °C for 30 min. The mixture was then gradually warmed to room temperature. After the mixture was stirred for 2 h, it was poured into H_2O (30 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was successively washed with H_2O (30 mL) and brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (26:74 EtOAc–hexane) gave **16** (76.8 mg, 84%) as an oil: ^1H NMR (500 MHz, $CDCl_3$) δ 1.64 (d, 1H, *J* = 6.7 Hz, C1S*H*), 3.21 (t, 1H, *J* = 8.4 Hz, C6′*H*H), 3.33 (dd, 1H, *J* = 5.4, 8.4 Hz, C6′*H*H), 3.63 (dd, 1H, *J* = 3.3, 9.5 Hz, C3*H*), 3.65, 3.74, 3.76 (each s, 3H, OC*H*$_3$), 3.78–3.83 (8H, C3′*H*, C1*H*, OC*H*$_3$ × 2), 3.86 (br d, 1H, *J* = 15.6 Hz, C6*H*H), 3.88 (dd, 1H, *J* = 3.5, 10.2 Hz, C2′*H*), 3.95 (dd, 1H, *J* = 4.9, 9.5 Hz, C2*H*), 3.98 (br d, 1H, *J* = 15.6 Hz, C6*H*H), 4.15 (br s, 1H, C4′*H*), 4.17 (d, 1H, *J* = 3.3 Hz, C4*H*), 4.34–4.40 (4H, ArC*H*HO × 4), 4.45 (br dd, 1H, *J* = 5.4, 8.4 Hz, C5′*H*), 4.47 (d, 1H, *J* = 12.9 Hz, ArC*H*-HO), 4.57 (s, 2H, ArC*H*$_2$O), 4.59, 4.63 (each d, 1H, *J* = 11.8 Hz, ArC*H*-HO), 4.77 (d, 1H, *J* = 10.4 Hz, ArC*H*HO), 4.93 (d, 1H, *J* = 3.5 Hz, C1′*H*), 5.48 (br d, 1H, *J* = 4.3 Hz, C5a*H*), 6.67 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.71 (4H, *aromatic protons*), 6.85 (4H, *aromatic protons*), 6.96 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.06 (br d, 2H, *J* = 8.5 Hz, *aromatic protons*), 7.13–7.20 (20H, *aromatic protons*), 7.25 (4H, *aromatic protons*), 7.29 (6H, *aromatic protons*), 7.36 (6H, *aromatic protons*). This sample was immediately used for the next coupling reaction with **19**.

3.17. Methyl 2,3-di-*O*-(4-methoxyphenylmethyl)-α-D-glucopyranoside (18)

Sodium hydride (washed with hexane 2.00 g, 83.3 mmol) was added slowly to a DMF solution (50 mL) of methyl 4,6-*O*-(4-methoxybenzylidene)-α-D-glucopyranoside (**17**)[21] (6.50 g, 20.8 mmol) at room temperature. Upon the addition of the substrate, H_2 gas evolved. After stirring for 10 min, 4-methoxybenzyl bromide (16.7 g, 83.1 mmol) was added at 0 °C. After stirring at 0 °C for 10 min, the cooling bath was removed and the mixture was stirred at room temperature for 20 min. Methanol (10 mL) and Et_3N (10 mL) were successively added to decompose the excess reagent. After stirring for an additional 30 min, the mixture was poured into H_2O (200 mL), and the aqueous layer was extracted with EtOAc (150 mL × 3). The organic layers were washed successively with H_2O (200 mL) and brine (200 mL), combined, dried over $MgSO_4$, and then concentrated in vacuo to give the crude solid. Recrystallization from 30:70 EtOAc–hexane gave methyl 4,6-*O*-(4-methoxybenzylidene)-2,3-*O*-di-(4-methoxyphenylmethyl)-α-D-glucopyranoside (9.30 g, 81%) as needles: mp 128 °C, $[\alpha]_D^{25}$ −41.2 (*c* 1.44, $CHCl_3$); IR (film) 2910, 1615, 1515, 1370, 1250, 1085, 1045, 1035, 825 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.38 (s, 3H, OC*H*$_3$), 3.50 (dd, 1H, *J* = 3.7, 9.3 Hz, C2*H*), 3.55 (t, 1H, *J* = 9.3 Hz, C4*H*), 3.67 (t, 1H, *J* = 10.2 Hz, C6*H*H), 3.78 (1H, C5*H*), 3.79, 3.80, 3.81 (each s, 3H, OC*H*$_3$), 3.99 (t, 1H, *J* = 9.3 Hz, C3*H*), 4.23 (dd, 1H, *J* = 4.8, 10.0 Hz, C6*H*H), 4.52 (d, 1H, *J* = 3.7 Hz, C1*H*), 4.62 (d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.73–4.82 (3H, ArC*H*HO × 3), 5.49 (s, 1H, ArC*H*), 6.83 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.90 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.28 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.29 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.40 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.22, 55.23, 55.26, 55.28 (each OCH$_3$), 62.32 (*C*5), 68.98 (*C*6), 73.37, 74.97 (each ArCH$_2$O), 78.27 (*C*3), 78.71 (*C*2), 82.05 (*C*4), 99.31

(*C*1), 101.20 (ArCH), 113.52, 113.69, 113.80, 127.31, 129.65, 129.70, 129.95, 130.27, 130.94, 159.15, 159.37, 159.96 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 575.2272 (3.9, calcd for $C_{31}H_{36}O_9Na$ $[M+Na]^+$: 575.2257), 553.2455 (100, calcd for $C_{31}H_{37}O_9$ $[M+H]^+$: 553.2438).

A solution of the product (6.20 g, 11.2 mmol) in 90% aq acetic acid (100 mL) was stirred at 60 °C for 10 min. After cooling, the mixture was concentrated in vacuo below 30 °C. Silica gel column chromatography of the residue (70:30 EtOAc–hexane) gave **18** as an oil: $[\alpha]_D^{24}$ +5.4 (*c* 1.65, $CHCl_3$); IR (film) 3465, 2930, 1610, 1510, 1250, 1090, 1050, 1035, 820 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.98 (dd, 1H, *J* = 6.0, 6.6 Hz, C6O*H*), 2.32 (d, 1H, *J* = 2.6 Hz, C4O*H*), 3.37 (s, 3H, OCH_3), 3.44–3.49 (2H, C2*H*, C4*H*), 3.59 (dt, 1H, *J* = 4.1, 9.7 Hz, C5*H*), 3.69–3.79 (3H, C3*H*, C6H_2), 3.796, 3.802 (each s, 3H, OCH_3), 4.54 (d, 1H, *J* = 3.5 Hz, C1*H*), 4.59 (d, 1H, *J* = 11.8 Hz, ArC*H*-HO), 4.61 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.71 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.93 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 6.87 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.88 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.28 (4H, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.22 (OCH_3), 55.24 (OCH_3 × 2), 62.50 (*C*6), 70.43 (*C*4), 70.65 (*C*5), 72.77, 74.93 (each ArCH_2O), 79.42 (*C*2), 80.87 (*C*3), 98.27 (*C*1), 113.87, 114.03, 129.60, 129.69, 130.08, 130.83, 159.37, 159.45 (*aromatic carbons*); ESIMS (%, rel. int.) *m*/*z*: 457.1838 (18, calcd for $C_{23}H_{30}O_8Na$ $[M+Na]^+$: 457.1833), 452.2285 (100, calcd for $C_{23}H_{34}NO_8$ $[M+NH_4]^+$: 452.2284).

3.18. Allyl (methyl 2,3-di-*O*-(4-methoxyphenylmethyl)-4-*O*-trifluoromethanesulfonyl-α-D-glucopyranosid)uronate (19)

A suspension of **18** (500 mg, 1.20 mmol) in a mixture of CH_2Cl_2 (10 mL) and H_2O (5.0 mL) was stirred with $PhI(OAc)_2$ (1.20 g, 3.61 mmol) and 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO, 56.0 mg, 358 μmol) at room temperature for 20 min. Aq 10% $Na_2S_2O_3$ (2.0 mL) was added, the mixture was poured into H_2O (100 mL), and the aqueous layer was extracted with EtOAc (100 mL × 3). The combined extract was washed with brine (100 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue with EtOAc gave the carboxylic acid (434 mg, 84%) as an oil: $[\alpha]_D^{25}$ +7.3 (*c* 1.83, $CHCl_3$); IR (film) 3470, 2935, 1740, 1610, 1510, 1250, 1110, 1055, 820 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.40 (s, 3H, OCH_3), 3.48 (dd, 1H, *J* = 3.4, 9.4 Hz, C2*H*), 3.71 (dd, 1H, *J* = 8.6, 9.6 Hz, C2*H*), 3.79, 3.80 (each s, 3H, OCH_3), 3.81 (1H, C3*H*), 4.12 (d, 1H, *J* = 9.6 Hz, C5*H*), 4.57 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.60 (d, 1H, *J* = 3.4 Hz, C1*H*), 4.73 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.74 (d, 1H, *J* = 10.9 Hz, ArC*H*HO), 4.82 (d, 1H, *J* = 10.9 Hz, ArC*H*HO), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.87 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.26 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.29 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.22 (OCH_3 × 2), 55.95 (OCH_3), 69.66 (*C*5), 71.66 (*C*4), 73.23, 75.11 (each ArCH_2O), 77.97 (*C*2), 79.98 (*C*3), 98.65 (*C*1), 113.87 (×2), 129.66, 129.76, 129.91, 130.60, 159.28, 159.46 (*aromatic carbons*), 172.97 (*C*═O); ESIMS (%, rel. int.) *m*/*z*: 471.1645 (38, calcd for $C_{23}H_{28}O_9Na$ $[M+Na]^+$: 471.1631), 466.2087 (100, calcd for $C_{23}H_{32}NO_9$ $[M+NH_4]^+$: 466.2077).

A solution of the product (434 mg, 968 μmol), allyl alcohol (169 mg, 2.91 mmol), and 1-hydroxybenzotriazole monohydrate (148 mg, 966 μmol) in CH_2Cl_2 (10 mL) was stirred with 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide hydrochloride (558 mg, 2.91 mmol) at room temperature for 1 h. The mixture was poured into aq HCl (5.0 mM, 50 mL), and the aqueous layer was extracted with EtOAc (50 mL × 3). The combined organic layer was washed with brine (50 mL), dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified with silica gel column chromatography (26:74 EtOAc–hexane) to give the allyl ester (411 mg, 68%) as an oil: $[\alpha]_D^{24}$ +9.7 (*c* 0.95, $CHCl_3$); IR (film) 3490, 2920, 1740, 1610, 1510, 1240, 1030, 985, 820 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.77 (d, 1H, *J* = 1.9 Hz, C4O*H*), 3.42 (s, 3H, OCH_3), 3.50 (dd, 1H, *J* = 3.3, 9.1 Hz, C2*H*), 3.77–3.80 (2H, C3*H*, C4*H*), 3.800, 3.802 (each s, 3H, OCH_3), 4.15 (d, 1H, *J* = 9.6 Hz, C5*H*), 4.58 (d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.61 (d, 1H, *J* = 3.3 Hz, C1*H*), 4.68 (2H,CH_2CHCH_2O), 4.70 (d, 1H, *J* = 11.0 Hz, ArC*H*HO), 4.73 (d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.83 (d, 1H, *J* = 11.0 Hz, ArC*H*HO), 5.25 (ddd, 1H, *J* = 1.1, 2.5, 10.4 Hz, C*H*HCHCH_2O), 5.34 (ddd, 1H, *J* = 1.5, 2.5, 17.3 Hz, C*H*HCHCH_2O), 5.91 (1H, CH_2CHCH_2O), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.87 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.27 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.29 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*); ^{13}C NMR (100 MHz, $CDCl_3$) δ 55.26 (OCH_3 × 2), 55.85 (OCH_3), 66.15 (CH_2CHCH_2O), 70.76 (*C*5), 71.67 (*C*4), 73.22, 75.03 (each ArCH_2O), 78.09 (*C*2), 79.99 (*C*3), 98.75 (*C*1), 113.89, 113.93 (*aromatic carbons*), 119.14 (CH_2CHCH_2O), 129.59, 129.79, 130.02, 130.75 (*aromatic carbons*), 131.26 (CH_2CHCH_2O), 159.33, 159.49 (*aromatic carbons*), 169.79 (*C*═O); ESIMS (%, rel. int.) *m*/*z*: 511.1934 (15, calcd for $C_{26}H_{32}O_9Na$ $[M+Na]^+$: 511.1944), 506.2378 (100, calcd for $C_{26}H_{36}NO_9$ $[M+NH_4]^+$: 506.2390).

To a solution of the product (80.0 mg, 164 μmol) in a mixture of pyridine (38.0 mg, 480 μmol) and CH_2Cl_2 (2.0 mL), trifluoromethanesulfonic anhydride (67.7 mg, 240 μmol) was added at 0 °C. After stirring for 10 min, the mixture was poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. The residue was purified with silica gel column chromatography (20:80 EtOAc–hexane) to give **19** (98.0 mg, 96%) as an oil: ^1H NMR (400 MHz, $CDCl_3$) δ 3.41 (s, 3H, OCH_3), 3.58 (dd, 1H, *J* = 3.4, 9.5 Hz, C2*H*), 3.81 (s, 6H, OCH_3 × 2), 4.02 (t, 1H, *J* = 9.5 Hz, C3*H*), 4.37 (d, 1H, *J* = 10.2 Hz, C5*H*), 4.50 (d, 1H, *J* = 3.4 Hz, C1*H*), 4.51 (d, 1H, *J* = 10.8 Hz, ArC*H*HO), 4.61, 4.71 (each ddd, 1H, *J* = 1.2, 6.0, 13.0 Hz, $CH_2CHCHHO$), 4.73 (d, 1H, *J* = 10.8 Hz, ArC*H*HO), 4.74, 4.83 (each d, 1H, *J* = 9.9 Hz, ArC*H*HO), 4.87 (dd, 1H, *J* = 9.5, 10.2 Hz, C4*H*), 5.29 (ddd, 1H, *J* = 1.2, 2.3, 10.3 Hz, C*H*HCHCH_2O), 5.36 (ddd, 1H, *J* = 1.2, 2.3, 17.2 Hz, C*H*HCHCH_2O), 5.91 (ddt, 1H, *J* = 6.0, 10.3, 17.2 Hz, CH_2CHCH_2O), 6.86 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.87 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 7.24 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.29 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*). This sample was immediately used for the next coupling reaction.

3.19. Allyl 2,3,4-tri-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-α-D-galactopyranosyl-(1→4)-[2,3-di-*O*-(4-methoxyphenylmethyl)-6-*O*-triphenylmethyl-1-thio-α-$\Delta^{5,5a}$-carba-D-galactopyranosyl]-(1→4)-[methyl 2,3-di-*O*-(4-methoxyphenylmethyl)-α-D-galactopyranosid]uronate (20)

A mixture of **16** (76.8 mg, 53.3 μmol) and **19** (66.0 mg, 106 μmol) in DMF (2.5 mL) was stirred with NaH (1.5 mg, 63 μmol) at room temperature for 20 min. The mixture was poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed successively with H_2O (30 mL) and brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (6:94 EtOAc–benzene) gave **20** (36.7 mg, 36%) along with recovered **16** (31.5 mg, 41%), as oils. The ^1H NMR spectrum of the recovered **16** was identical to that of the authentic sample as described in Section 3.16.

3.19.1. Physicochemical and spectral data for 20

$[\alpha]_D^{25}$ +49.3 (*c* 1.25, $CHCl_3$); IR (film) 2930, 1760, 1610, 1510, 1250, 1090, 1035, 820, 700 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 3.18 (t, 1H, *J* = 8.3 Hz, C6″*H*H), 3.31 (dd, 1H, *J* = 5.4, 8.3 Hz, C6″*H*H), 3.36, 3.65, 3.67 (each s, 3H, OCH_3), 3.71–3.77 (18H,

C3″*H*, C3′*H*, C6′*H*H, OCH_3 × 5), 3.81 (dd, 1H, *J* = 3.4, 10.3 Hz, C2″*H*), 3.86 (br d, 1H, *J* = 13.9 Hz, C6′*H*H), 3.89 (1H, C4*H*), 3.94 (1H, C1′*H*), 4.02 (1H, C2′*H*), 4.06–4.08 (2H, C3*H*, C4″*H*), 4.11–4.14 (2H, C2*H*, C4′*H*), 4.18, 4.22 (each d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.33 (d, 1H, *J* = 10.5 Hz, ArC*H*HO), 4.38 (1H, C5″*H*), 4.41 (d, 1H, *J* = 12.4 Hz, ArC*H*HO), 4.49–4.53 (6H, $CH_2CHCHHO$, ArC*H*HO, ArCH_2O × 2), 4.56 (d, 1H, *J* = 10.8 Hz, ArC*H*HO), 4.58 (d, 1H, *J* = 11.7 Hz, ArC*H*HO), 4.60 (d, 1H, *J* = 3.6 Hz, C1*H*), 4.639 (d, 1H, *J* = 2.1 Hz, C5*H*), 4.641 (d, 1H, *J* = 11.7 Hz, ArC*H*HO), 4.75 (d, 1H, *J* = 10.5 Hz, ArC*H*HO), 4.78 (d, 1H, *J* = 10.8 Hz, ArC*H*HO), 4.83 (d, 1H, *J* = 3.4 Hz, C1″*H*), 4.86 (br dd, 1H, *J* = 5.5, 12.7 Hz, $CH_2CHCHHO$), 5.20 (br dd, 1H, *J* = 1.2, 10.4 Hz, C*H*H$CHCH_2O$), 5.30 (br dd, 1H, *J* = 1.2, 17.2 Hz, C*H*H$CHCH_2O$), 5.88 (1H, C5a′*H*), 5.94 (ddt, 1H, *J* = 5.5, 10.4, 17.2 Hz, CH_2CHCH_2O), 6.69 (6H, *aromatic protons*), 6.77 (4H, *aromatic protons*), 6.80 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 6.85 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.93 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 6.99 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.09–7.36 (40H, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) *δ* 47.00 (*C*1′), 50.26 (*C*4), 55.08 (OCH_3 × 3), 55.18 (OCH_3 × 4), 55.95 (OCH_3), 62.07 (*C*6″), 64.51 (*C*6′), 65.88 (CH_2CHCH_2O), 70.07 (*C*5″), 70.37 (*C*5), 72.13, 72.30, 72.35, 72.42, 72.62, 73.53, 73.97 (each ArCH_2O), 75.08 (*C*4′, *C*4″), 75.26 (*C*2″), 75.77 (*C*2), 76.19 (*C*3′), 77.37 (*C*3, *C*2′), 78.89 (*C*3″), 86.62, 87.10 (each *C*Ph$_3$), 98.93 (*C*1″), 99.58 (*C*1), 113.30, 113.49, 113.56, 113.61, 113.66, 113.77, 113.82 (*aromatic carbons*), 118.92 (CH_2CHCH_2O), 125.04 (*C*5a′), 126.93 (×2), 127.73, 127.77, 128.57, 128.71, 128.75, 129.05, 129.13 (×2), 129.47, 129.55, 129.85, 130.38, 130.49 (×2), 130.93, 131.02, 131.08, 131.14 (*aromatic carbons*), 131.92 (CH_2CHCH_2O), 135.18 (*C*5′), 143.76, 144.24, 158.81 (×2), 158.87 (×2), 158.96, 159.00, 159.30 (*aromatic carbons*), 168.15 (*C*═O); ESIMS (%, rel. int.) *m*/*z*: 1931.7912 (21, calcd for $C_{117}H_{120}O_{22}SNa$ $[M+Na]^+$: 1931.7890), 1926.8204 (72, calcd for $C_{117}H_{124}NO_{22}S$ $[M+NH_4]^+$: 1926.8336).

3.20. Allyl 2,3,4-Tri-*O*-(4-methoxyphenylmethyl)-α-D-galacto-pyranosyl-(1→4)-[2,3-di-*O*-(4-methoxyphenylmethyl)-1-thio-α-$\Delta^{5,5a}$carba-D-galactopyranosyl]-(1→4)-[methyl 2,3-di-*O*-(4-methoxyphenylmethyl)-α-D-galactopyranosid]urinate (21)

To a solution of **20** (36.7 mg, 19.2 μmol) in a mixture of CH_2Cl_2 (2.0 mL) and MeOH (1.0 mL), 90% aqueous formic acid (0.5 mL) was added at 0 °C. After stirring at 0 °C for 1 h, the cooling bath was removed. After the mixture was stirred at room temperature for additional 1 h, satd aq $NaHCO_3$ solution (2.0 mL) was added. The mixture was then poured into H_2O (20 mL) and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo. Silica gel column chromatography of the residue (50:50 EtOAc–hexane) gave **21** (20.0 mg, 73%) as an oil. $[\alpha]_D^{26}$ +96.5 (*c* 1.24, $CHCl_3$); IR (film) 3465, 2940, 1760, 1610, 1510, 1460, 1250, 1090, 1035, 820 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) *δ* 1.67 (1H, C6″O*H*), 3.25 (ddd, 1H, *J* = 4.9, 5.1, 11.3 Hz, C6″*H*H), 3.35 (s, 3H, OCH_3), 3.48 (ddd, 1H, *J* = 1.5, 6.7, 11.3 Hz, C6″*H*H), 3.57 (2H, C5″*H*, C4*H*), 3.67 (2H, C4″*H*, C1′*H*), 3.72 (dd, 1H, *J* = 3.4, 5.6 Hz, C3′*H*), 3.75 (s, 3H, OCH_3), 3.77–3.86 (21H, C6′*H*H, C2′*H*, C3″*H*, OCH_3 × 6), 3.91 (dd, 1H, *J* = 3.7, 9.9 Hz, C2*H*), 3.95 (1H, C6′*H*H), 3.98 (dd, 1H, *J* = 3.6, 10.1 Hz, C2″*H*), 4.05 (dd, 1H, *J* = 4.0, 9.9 Hz, C3*H*), 4.37 (d, 1H, *J* = 11.8 Hz, ArC*H*HO), 4.40 (1H, C4′*H*), 4.42–4.48 (31H, ArC*H*HO × 2, $CH_2CHCHHO$), 4.52 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.56 (d, 1H, *J* = 11.7 Hz, ArC*H*HO), 4.58 (d, 1H, *J* = 11.7 Hz, ArC*H*HO), 4.59 (d, 1H, *J* = 3.7 Hz, C1*H*), 4.61–4.70 (5H, ArC*H*HO × 3, C5*H*, $CH_2CHCHHO$), 4.72 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 4.74 (d, 1H, *J* = 11.2 Hz, ArC*H*HO), 4.77 (d, 1H, *J* = 11.7 Hz, ArC*H*HO), 4.79 (d, 1H, *J* = 3.6 Hz, C1″*H*), 4.81 (d, 1H, *J* = 11.9 Hz, ArC*H*HO), 4.87 (d, 1H, *J* = 11.3 Hz, ArC*H*HO), 5.15 (br dd, 1H, *J* = 1.2, 10.4 Hz, C*H*H$CHCH_2O$), 5.24 (br dd, 1H, *J* = 1.4, 17.2 Hz, C*H*H$CHCH_2O$), 5.88 (2H, C5a′*H*, CH_2CHCH_2O), 6.77 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*), 6.84–6.87 (10H, *aromatic protons*), 6.90 (br d, 2H, *J* = 8.7 Hz, *aromatic protons*), 7.14 (br d, 2H, *J* = 8.6 Hz, *aromatic protons*), 7.21 (4H, *aromatic protons*), 7.28 (6H, *aromatic protons*), 7.32 (br d, 2H, *J* = 8.8 Hz, *aromatic protons*); ^{13}C NMR (125 MHz, $CDCl_3$) *δ* 47.78 (*C*1′), 52.47 (*C*4), 55.18, 55.19, 55.22 (each OCH_3), 55.24 (OCH_3 × 2), 55.25 (OCH_3 × 2), 55.95 (OCH_3), 62.54 (*C*6″), 64.60 (*C*6′), 65.90 (CH_2CHCH_2O), 70.76 (*C*5), 70.88 (*C*5″), 72.46, 72.73, 73.15, 73.41, 73.47, 73.85, 73.91 (each ArCH_2O), 74.91 (*C*4″), 75.20 (*C*2″), 76.20 (*C*3), 76.48 (*C*2 or *C*2′), 76.52 (*C*2 or *C*2′), 76.66 (*C*3′), 77.70 (*C*4′), 78.67 (*C*3″), 99.33 (*C*1), 101.08 (*C*1″), 113.67, 113.77, 113.79, 113.80, 113.82, 113.85, 113.87 (*aromatic carbons*), 119.00 (CH_2CHCH_2O), 127.31 (*C*5a′), 129.14, 129.28, 129.49, 129.59, 129.74, 129.90, 130.00, 130.21, 130.24, 130.30, 130.31 (×2), 130.50, 130.56 (*aromatic carbons*), 131.56 (CH_2CHCH_2O), 135.79 (*C*5′), 159.09, 159.18, 159.20, 159.30, 159.35, 159.37, 159.48 (*aromatic carbons*), 168.35 (*C*═O); ESIMS (%, rel. int.) *m*/*z*: 1447.5707 (15, calcd for $C_{79}H_{92}O_{22}SNa$ $[M+Na]^+$: 1447.5699), 1442.5117 (100, calcd for $C_{79}H_{96}NO_{22}S$ $[M+NH_4]^+$: 1442.6145).

3.21. (α-D-Galactopyranosyluronic acid)-(1→4)-(1-thio-α-$\Delta^{5,5a}$-carba-D-galactopyranosyluronic acid)-(1→4)-methyl α-D-galactopyranosid)uronic acid (2)

Oxalyl chloride (24.0 mg, 189 μmol) was added to a solution of dimethyl sulfoxide (29.6 mg, 379 μmol) in CH_2Cl_2 (1.0 mL) at −78 °C. After the mixture was stirred for 10 min, a solution of **21** (45.0 mg, 31.6 μmol) in CH_2Cl_2 (1.5 mL) was added at −78 °C, and the resulting mixture was stirred at the same temperature for 40 min. After triethylamine (57.6 mg, 569 μmol) was added, the cooling bath was removed. The mixture was further stirred at room temperature for 20 min. It was then poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine (30 mL), dried over $MgSO_4$, and then concentrated in vacuo to give the crude aldehyde that was immediately diluted with a mixture of 2-methyl-2-propanol (1.0 mL) and 2-methyl-2-butene (66.4 mg, 0.95 mmol). Sodium dihydrogenphosphate dihydrate (69.0 mg, 442 μmol) and sodium chlorite (29.0 mg, 321 μmol) were successively added at room temperature. Since the substrate was insoluble under these conditions, the reaction did not proceed. In order to dissolve it, 2-methyl-2-propanol (5.0 mL) was added, and the reaction proceeded. After stirring for 15 min, the mixture was poured into H_2O (20 mL), and the aqueous layer was extracted with EtOAc (15 mL × 3). The combined organic layer was washed with brine (15 mL), dried over $MgSO_4$, and then concentrated in vacuo. The residue was passed through a silica gel pad to give the crude **22**, which was dissolved in THF (1.4 mL) without purification. After the solution was stirred with tetrakis(triphenylphosphine)palladium (3.7 mg, 3.2 μmol) in the presence of pyrrolidine (9.0 mg, 130 μmol) at room temperature for 15 min, the mixture was concentrated in vacuo to give the crude tricarboxylic acid. A suspension of the crude product in a mixture of CH_2Cl_2 (1.0 mL) and H_2O (100 μL) was stirred with DDQ (108 mg, 476 μmol) at room temperature for 36 h. The mixture was poured into water (10 mL), and the aqueous layer was washed with EtOAc (10 mL × 2). The aqueous solution was concentrated in vacuo. After dilution with small amount of H_2O (ca. 0.3 mL), the resulting solution, which contained small amount of impurities based on its ^{1}H NMR spectrum, was loaded on a ODS Sep-Pak® cartridge (5.0 g) to give **2** (16.2 mg, 90%). HPLC (Inertsil® DIOL, 10 × 250 mm, 10:90:0.01 H_2O–CH_3CN–TFA, 3.0 mL/min flow, t_R = 50 min) gave a pure **2**: $[\alpha]_D^{24}$ +64.7 (*c* 1.60, D_2O); ^{1}H NMR (500 MHz, $CDCl_3$) *δ* 3.56 (s, 3H, OCH_3), 3.91 (2H, C2*H*, C4*H*), 3.94 (dd, 1H, *J* = 4.0, 10.3 Hz, C2″*H*), 4.06 (dd, 1H, *J* = 3.4, 10.3 Hz, C3″*H*), 4.14 (dd, 1H, *J* = 3.9, 9.1 Hz, C3′*H*), 4.23 (dd, 1H, *J* = 4.1, 5.0 Hz, C1′*H*), 4.35 (dd,

1H, J = 4.4, 10.2 Hz, C3H), 4.39 (dd, 1H, J = 5.0, 9.1 Hz, C2′H), 4.49 (dd, 1H, J = 1.3, 3.4 Hz, C4″H), 4.87 (d, 1H, J = 3.9 Hz, C4′H), 4.98 (d, 1H, J = 2.1 Hz, C5H), 5.03 (d, 1H, J = 4.1 Hz, C1H), 5.08 (d, 1H, J = 1.3 Hz, C5″H), 5.47 (d, 1H, J = 4.0 Hz, C1″H), 7.30 (d, 1H, J = 4.1 Hz, C5a′H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 50.87 (C1′), 54.70 (C4), 58.22 (OCH_3), 70.44 (C2″), 70.85 (C2′), 71.12 (C3″), 71.43 (C3″), 71.52 (C2), 71.68 (C3′), 72.63 (C4″), 72.72 (C5), 73.58 (C5″), 76.26 (C4′), 102.17 (C1″, C1), 130.82 (C5a′), 144.41 (C5′), 172.01, 175.35, 175.49 (each C═O); ESIMS (%, rel. int.) m/z: 595.0954 (100, calcd for $C_{20}H_{28}O_{17}SNa$ $[M+Na]^+$: 595.0945), 590.1391 (56, calcd for $C_{20}H_{32}NO_{17}S$ $[M+NH_4]^+$: 590.1391).

3.22. *endo*-PG1 inhibitory activity

An aqueous solution of tetragalacturonic acid[†] (32.8 nmol) and the analogue **2** (32.8 nmol) in H_2O (100 μL) was incubated at 30 °C for 5 min. Then *endo*-PG 1 solution (5.9 unit[27]) was added, and the mixture was incubated for another 12 h at 30 °C. After a small portion of the solution (10 μL) was sampled and passed through a Dowex-50 W column to quench the reaction, the remaining tetragalacturonic acid was determined by HPLC (Shodex Sugar SH1821 Column (8 × 300 mm) with aq 0.005 N H_2SO_4 as eluent, flow rate of 3.0 mL/min, absorption at 210 nm.).

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.carres.2009.12.024.

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[†] Trigalacturonic acid was not used as the natural substrate, because most of trigalacturonic acid was not hydrolyzed by *endo*-PG1.