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Interplay of Protecting Groups and Side Chain Conformation in Glycopyranosides. Modulation of the Influence of Remote Substituents on Glycosylation?

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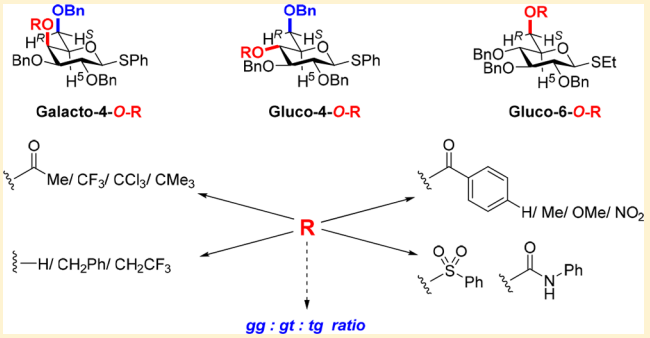
Supporting Information

ABSTRACT: The synthesis and conformational analysis of a series of phenyl 2,3,6-tri-*O*-benzyl-*β*-D-thio galacto- and glucopyranosides and their 6*S*-deuterio isotopomers, with systematic variation of the protecting group at the 4-position, are described. For the galactopyranosides, replacement of a 4-*O*-benzyl ether by a 4-*O*-alkanoyl or aroyl ester results in a small but measurable shift in side chain population away from the *trans,gauche* conformation and in favor of the *gauche,trans* conformer. In the glucopyranoside series on the other hand, replacement of a 4-*O*-benzyl ether by a 4-*O*-alkanoyl or aroyl ester results in a small but measurable increase in the population of the *trans,gauche* conformer at the expense of the *gauche,gauche* conformer. The possible modulating effect of these conformational changes on the well-known changes in the anomeric reactivity of glycosyl donors as a function of protecting group is discussed, raising the possibility that larger changes may be observed at the transition state for glycosylation. A comparable study with a series of ethyl 2,3,4-tri-*O*-benzyl-*β*-D-thioglucopyranosides reveals that no significant influence in side chain population is observed on changing the O6 protecting group.



INTRODUCTION

In carbohydrate chemistry, it is widely understood that anomeric reactivity is strongly influenced by the relative configuration of the complete set of stereogenic centers in the backbone.[1] Thus, for example, galactopyranosides undergo both acid-catalyzed and spontaneous hydrolysis more rapidly than their gluco isomers (Figure 1);[2−5] the same pattern of

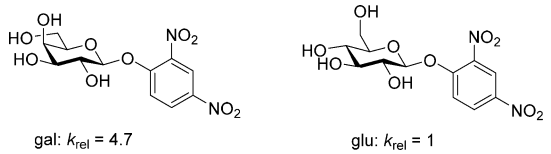


Figure 1. Relative rates of spontaneous hydrolysis of galacto- and glucopyranosides in water at 37 °C.[5]

reactivity is found in glycosylation reactions with a series of comparably protected thioglycosides.[6] The influence of protecting groups on the anomeric reactivity of glycosyl donors also is broadly appreciated, with the more electron-withdrawing (or disarming) esters retarding reaction rates compared to the less electron-withdrawing (or arming) ethers.[6−11]

Ring conformation is another important factor in anomeric reactivity. Thus, for any given configuration, ring conformations that maximize the number of axial (or pseudoaxial) C−O bonds generally exhibit the greatest anomeric reactivity (Figure 2).[12−15] The influence of configuration and ring conformation

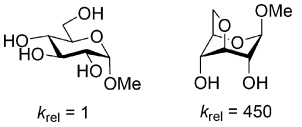


Figure 2. Influence of ring conformation on the hydrolysis of axial methyl glucosides in 2 M HCl at 60 °C.[4,15]

on anomeric reactivity is best explained by the ability of axial C−O bonds to stabilize nascent positive charge at the anomeric center as compared to their equatorial counterparts.[16−19]

The conformation of the side chain, defined as *gauche,gauche* (*gg*), *gauche,trans* (*gt*), or *trans,gauche* (*tg*) where the first and second terms refer to the position of O6 relative to O5 and C4, respectively,[20−22] is also increasingly recognized as influencing anomeric reactivity. Thus, the *trans,gauche* conformation exerts maximum retardation due to the strongly electron-withdrawing antiperiplanar relationship of the C6−O6 and the C5−O5 bonds (Figure 3).[23−25] The interplay between the conformation of the side chain and the glycosidic bond is further

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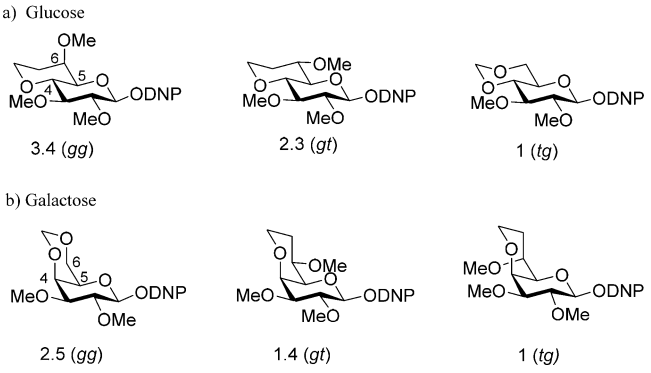


Figure 3. Influence of the *gauche,gauche* (*gg*), *gauche,trans* (*gt*), and *trans,gauche* (*tg*) side chain conformations on the relative rates of spontaneous hydrolysis of 2,4-dinitrophenyl glycosides in water at 37 °C.[23,24]

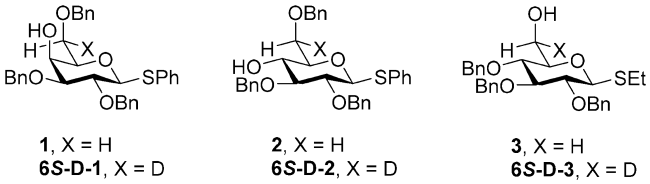
apparent from the work of Vázquez and co-workers in which it is demonstrated by CD and NMR methods that both the anomeric configuration and the nature of the aglycone influence the population of the different side chain conformers.[26−30]

In this Article, we begin to explore the possibility that protecting groups, in addition to their well-known influence on glycoside reactivity as a function of their electron-withdrawing ability,[1,7−11] also exert an indirect influence on anomeric reactivity by modulating the conformation of the side chain. To this end, we describe the preparation of a series of galacto and gluco thiopyranosides and, to facilitate spectral assignment, their 6*S*-deuterio isotopomers and study the conformation of the side chain as a function of protecting group at either the 4- or the 6-position. We show that the side chain population in a series of phenyl 2,3,6-tri-*O*-benzyl-β-D-thiogalacto- and glycopyranosides does indeed vary in a systematic manner on changing the functionality at the 4-position from a hydroxyl group to an ether and to an ester, albeit in a different manner in the two configurations. While these protecting-group-induced changes in conformation are small, they open the possibility that larger changes might arise at the transition state for glycosylation and thus open alternative avenues for the explanation of remote protecting group effects.

RESULTS AND DISCUSSION

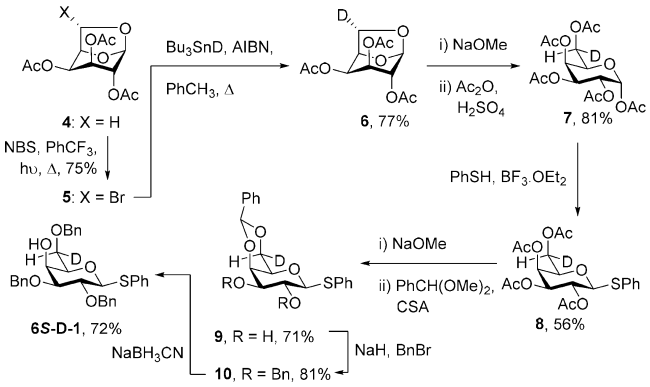
Experimental Design and Synthesis. In this investigation, we focus on the interplay between the protecting groups at O4 and O6 in the gluco- and galactopyranosides as the strongest candidates for observation of any changes in side chain conformation due to these interactions. Judging that the interaction in question could be probed through the variation of the O4 protecting group in the presence of a fixed O6 protecting group, or the inverse, we prepared phenyl 2,3,6-tri-*O*-benzyl-β-D-thiogalactopyranoside (**1**),[31] phenyl 2,3,6-tri-*O*-benzyl-β-D-thioglucopyranoside (**2**),[32] and ethyl 2,3,4-tri-*O*-benzyl-β-D-thioglucopyranoside (**3**)[33] by standard means. The use of the ethyl thioglycoside in **3** as opposed to the phenyl thioglycosides **1** and **2** was a matter of experimental convenience and was not expected to affect the analysis of side chain conformations, as is borne out by the subsequent results.

As the rigorous assignment of the diastereotopic pro-*R* and pro-*S* hydrogens at the 6-position of **1**−**3** and their derivatives

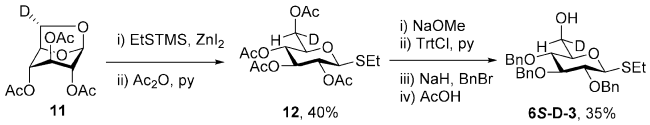


is critical to the correct conformational analysis of their side chains,[20] we also prepared 6*S*-deuterio **1**−**3** as outlined in Schemes 1 and 2. Thus, preferring a longer but unambiguous

Scheme 1. Synthesis of Phenyl 2,3,6-Tri-*O*-benzyl-6*S*-deuterio-β-D-thiogalactopyranoside (6*S*-D-1)



Scheme 2. Synthesis of Ethyl 2,3,4-Tri-*O*-benzyl-6*S*-deuterio-β-D-thioglucopyranoside (6*S*-D-3)



route based on exoselective quenching of radicals at the 6-position of 1,6-anhydropyranoses[34−38] over shorter routes involving asymmetric reduction of 6-aldehydo-sugars,[39−41] 2,3,4-tri-*O*-acetyl-1,6-anhydro-D-galactose (**4**) was subjected to white-light-mediated bromination with *N*-bromosuccinimide to give the exo-bromide **5** in good yield. This transformation follows the literature description[36] with the exception that the original solvent, tetrachloromethane, was replaced by the more environmentally friendly α,α,α-trifluoromethylbenzene[42] as described previously for the gluco series.[43] Reductive debromination with tributyltin deuteride, prepared according to Neumann,[44] then gave the 6*S*-deuterio anhydrogalactose (**6**) in 77% yield. A series of standard transformations were then applied to convert **6** via intermediates **7**−**10** to the desired **6*S*-D-1** uneventfully (Scheme 1). The 6*S*-deuterio analogue of **2** was prepared by inversion of **6*S*-D-1** by triflate formation, displacement with sodium benzoate, and saponification as reported in detail in the Experimental Section.

The 6*S*-deuterio-1,6-anhydroglucose derivative (**11**)[34,35,43] was the starting material for the preparation of **6*S*-D-3**. Thus, **11** was converted to the thioglycoside **12** by cleavage of the 1,6-anhydro bridge with trimethylsilyl ethanethiol in the presence of zinc iodide[45] followed by acetylation (Scheme 2). A series of standard reactions were then employed to convert **12** to the tribenzyl ether **6*S*-D-3** as described previously for the nondeuterated isotopomer[33] (Scheme 2).

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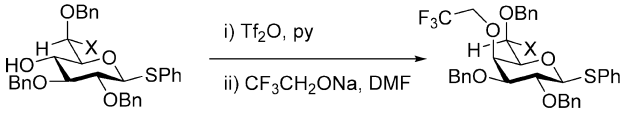
The thiogalactoside **1** and its 6*S*-monodeuterio isotopomer were converted to a series of esters **13**–**20** at the 4-position as well as to the benzyl ether **21** by standard methods as described in the Experimental Section. The 4-*O*-(2,2,2-trifluoroethyl) ether (**22**) and its 6*S*-deuterio analogue (**6*S*-D-22**) were obtained from **2** and 6*S*-deuterio **2** by triflation followed by displacement with sodium trifluoroethoxide in DMF (Scheme 3). The thioglucoside **2** and its 6*S*-monodeuterio isomer were also converted to the derivatives **23**–**27** by standard means, as described in the Experimental Section. Similarly, the thioglucoside **3** and its 6*S*-monodeuterio isotopomer were converted to the 6-*O*-esters **28**–**34**, the 6-*O*-carbamate **35**, and the 6-*O*-benzyl ether **36** by standard means, as described in the Experimental Section.

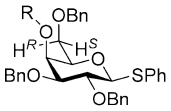
Scheme 3. Synthesis of Phenyl 2,3,6-Tri-*O*-benzyl-4-*O*-(2,2,2-trifluoroethyl)-*β*-D-thiogalactopyranoside (22) and Its 6*S*-Deuterio Analogue (6*S*-D-22)



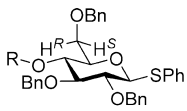
2, X = H
6*S*-D-2, X = D

22, X = H, 61%
6*S*-D-22, X = D, 30%

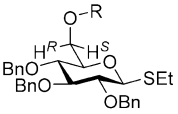
Measurement of NMR Spectra, Influence of Solvent, and Estimation of Errors in Coupling Constants. The ^{1}H NMR spectra of **1**–**3** and **13**–**36** were recorded in $CDCl_3$ and deuteriobenzene and fully assigned by the usual array of 1D- and 2D-NMR methods, with the distinction between the 6-pro-*R* and pro-*S* resonances, herein after H^{6R} and H^{6S}, made on the basis of comparison with the selectively 6*S*-deuterated analogues. All first order couplings were analyzed directly. For second order spectra, including those complicated by the presence of virtual coupling, the spin simulation tool in the MestReNova 9.0 suite of programs was used to extract first order coupling constants. The chemical shifts and so-obtained ^3J coupling constants in the H^5, H^{6R}, and H^{6S} spin systems are presented in Table 1 for the 4-*O*-substituted galacto series of compounds, in Table 2 for the corresponding 4-*O*-substituted gluco compounds, and in Table 3 for the 6-*O*-substituted gluco series of compounds. For ease of comparison, in each of Tables 1–3, the alcohols are listed first, followed by the ethers, and then the esters grouped according to patterns in the side chain conformations.



1, R = H
13, R = Ac
14, R = $COCMe_3$
15, R = $COCF_3$
16, R = $COCCl_3$
17, R = Bz
18, R = Bz-4-Me
19, R = Bz-4-OMe
20, R = Bz-4-NO_2
21, R = Bn
22, R = CH_2CF_3



2, R = H
23, R = Ac
24, R = $COCF_3$
25, R = Bz
26, R = SO_2Ph
27, R = Bn



3, R = H
28, R = Ac
29, R = $COCMe_3$
30, R = $COCF_3$
31, R = Bz
32, R = Bz-4-Me
33, R = Bz-4-OMe
34, R = Bz-4-NO_2
35, R = CONHPh
36, R = Bn

Inspection of the coupling constant data in Tables 1–3 reveals no systematic difference in coupling constants for any given system on changing from $CDCl_3$ to C_6D_6 consistent with an earlier study with rigid bicyclic models of galacto- and glucopyranosides,[46] from which we conclude that the side chain conformation is unaffected by the nature of the solvent ($CDCl_3$ or C_6D_6). It follows that data acquired in one of the two solvents can be extrapolated to the other solvent in cases for which resolution was insufficient to enable the determination of coupling constants in both solvents. Small non-systematic differences between solvents are found and permit the estimation of errors in the $^3J_{5,6R}$ and $^3J_{5,6S}$ coupling constants. For the 18 compounds (and hence 36 sets of coupling constants) in which both values could be measured in both solvents, differences in a given coupling constant are 0.4 Hz or less consistent with the digital resolution of 0.38 Hz, leading us to adopt 0.4 Hz as the error limit in these measurements. The differences in the $^3J_{5,6R}$ and $^3J_{5,6S}$ coupling constants of the phenyl and ethyl glycosides of 2,3,4,6-tetra-*O*-benzyl-*β*-D-thioglucopyranoside (**27** and **36**) (Tables 2 and 3, respectively) are less than the error limit and so substantiate the use of the different aglycones in the two series.

Calculation of Side Chain Populations and Estimation of Errors. With the aid of limiting $^3J_{R,gg}$–$^3J_{S,tg}$ coupling constants for the pure *gg*, *gt*, and *tg* conformers (Table 4), determined using a series of rigid bicyclic models,[46] the side chain populations (f_{gg}–f_{tg}) of all compounds were determined

Table 1. Pertinent ^{1}H Chemical Shifts, ^3J Coupling Constants, and Side Chain Populations for 1 and 13–22 in $CDCl_3$ and C_6D_6

		chem shift[a] (ppm)		$^3J_{5,6}$[a] (Hz)		population[a] (%)		
	4-*O*-Subs	H^{6R}	H^{6S}	$J_{5,6R}$	$J_{5,6S}$	*gg*	*gt*	*tg*
1	H	3.78 (3.72)	3.81 (3.75)	5.8 (6.1)	5.7 (5.8)	25.6 (21.9)	31.8 (34.4)	42.6 (43.7)
21	$PhCH_2$	3.65 (3.57)	3.67 (3.66)	nd (5.7)	nd (7.4)	nd (13.2)	nd (22.6)	nd (64.2)
22	CF_3CH_2	3.69 (3.55)	3.74 (3.68)	5.5 (5.7)	7.7 (7.6)	12.8 (11.7)	19.1 (21.7)	68.0 (66.7)
13	Ac	3.64 (3.47)	3.55 (3.42)	6.0 (6.1)	6.7 (6.5)	15.8 (16.4)	29.0 (31.0)	55.2 (52.6)
14	Me_3CCO	3.62 (3.49)	3.49 (3.42)	6.1 (6.0)	6.7 (6.8)	14.8 (15.0)	30.1 (28.6)	55.1 (56.4)
17	PhCO	3.69 (3.53)	3.59 (3.49)	5.8 (6.1)	6.8 (6.6)	17.0 (15.6)	26.5 (30.5)	56.5 (53.9)
18	*p*-MeC_6H_4CO	3.68 (3.56)	3.57 (3.52)	5.9 (6.2)	6.8 (6.5)	16.0 (15.4)	27.5 (32.0)	56.5 (52.5)
19	*p*-$MeOC_6H_4CO$	3.69 (3.57)	3.59 (3.54)	6.1 (6.2)	6.5 (6.4)	16.4 (16.2)	31.0 (32.5)	52.6 (51.3)
20	*p*-$O_2NC_6H_4CO$	3.69 (3.47)	3.56 (3.42)	5.7 (5.6)	7.2 (7.0)	14.8 (17.3)	23.6 (23.5)	61.6 (59.1)
15	CF_3CO	3.67 (3.39)	3.49 (3.36)	5.6 (5.7)	8.3 (8.1)	7.1 (7.7)	17.3 (19.2)	75.6 (73.0)
16	Cl_3CCO	3.71 (3.43)	3.59 (3.46)	5.7 (nd)	8.2 (nd)	6.9 (nd)	18.8 (nd)	74.3 (nd)

[a]Chemical shift, coupling constants, and populations in $CDCl_3$ (chemical shift, coupling constants, and populations in C_6D_6).

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Table 2. Pertinent ^{1}H Chemical Shifts, ^3J Coupling Constants, and Side Chain Populations for 2 and 23−27 in $CDCl_3$ and C_6D_6

		chem shift[a] (ppm)		$^3J_{5,6}$[a] (Hz)		population[a] (%)		
	4-*O*-Subs	H^{6R}	H^{6S}	$J_{5,6R}$	$J_{5,6S}$	*gg*	*gt*	*tg*
2	H	3.76 (3.60)	3.80 (3.64)	5.3 (5.3)	4.1 (3.7)	43.1 (46.2)	34.5 (36.4)	22.4 (17.4)
27	$PhCH_2$	3.73 (3.63)	3.80 (3.63)	4.8 (nd)	1.9 (nd)	65.2 (nd)	40.0 (nd)	−5.3 (nd)
23	Ac	3.58 (3.54)	3.58 (3.58)	nd (5.8)	nd (3.2)	nd (45.3)	nd (43.9)	nd (10.8)
25	PhCO	3.65 (3.58)	3.65 (3.62)	nd (6.0)	nd (2.9)	nd (45.7)	nd (47.3)	nd (7.0)
24	CF_3CO	3.58 (3.30)	3.61 (3.37)	4.7 (4.3)	3.6 (3.5)	52.9 (57.6)	30.8 (27.2)	16.3 (15.2)
26	$PhSO_2$	3.51 (3.69)	3.71 (3.81)	5.6 (5.3)	2.1 (2.0)	55.9 (59.6)	47.1 (44.6)	−3.0 (−4.2)

[a]Chemical shift, coupling constants, and populations in $CDCl_3$ (chemical shift, coupling constants, and populations in C_6D_6).

Table 3. Pertinent ^{1}H Chemical Shifts and ^3J Coupling Constants for 3 and 28−36 in $CDCl_3$ and C_6D_6

		chem shift[a] (ppm)		$^3J_{5,6}$[a] (Hz)		population[a] (%)		
	6-*O*-Subs	H^{6R}	H^{6S}	$J_{5,6R}$	$J_{5,6S}$	*gg*	*gt*	*tg*
3	H	3.71 (3.58)	3.87 (3.69)	4.8 (nd)	2.7 (nd)	59.0 (nd)	36.1 (nd)	4.9 (nd)
36	$PhCH_2$	3.69 (3.61)	3.76 (3.61)	5.0 (nd)	1.9 (nd)	63.3 (nd)	42.0 (nd)	−5.3 (nd)
28	Ac	4.20 (4.26)	4.33 (4.43)	5.4 (5.4)	2.4 (2.2)	55.5 (57.0)	43.7 (44.6)	0.9 (−1.7)
29	Me_3CCO	4.12 (4.23)	4.44 (4.55)	5.6 (5.7)	1.8 (2.1)	58.2 (54.9)	48.6 (48.2)	−6.8 (−3.0)
31	PhCO	4.46 (4.51)	4.65 (4.65)	nd (5.6)	nd (2.3)	nd (54.3)	nd (46.2)	nd (−0.5)
32	*p*-MeC_6H_4CO	4.40 (4.68)	4.59 (4.54)	5.5 (5.7)	2.2 (2.2)	56.1 (54.1)	45.6 (47.7)	−1.7 (−1.8)
33	*p*-$MeOC_6H_4CO$	4.58 (4.56)	4.41 (4.69)	5.5 (5.6)	2.3 (2.2)	55.3 (55.1)	45.2 (46.7)	−0.4 (−1.7)
34	*p*-$O_2NC_6H_4CO$	4.44 (4.40)	4.62 (4.56)	5.4 (5.6)	2.2 (2.3)	57.0 (54.3)	44.6 (46.2)	−1.7 (−0.5)
30	CF_3CO	4.32 (4.05)	4.54 (4.24)	6.3 (6.3)	2.1 (2.2)	49.0 (48.2)	54.2 (53.8)	−3.3 (−2.0)
35	PhNHCO	4.37 (4.46)	4.40 (4.43)	nd (4.6)	nd (2.5)	nd (62.5)	nd (35.1)	nd (2.4)

[a]Chemical shift, coupling constants, and populations in $CDCl_3$ (chemical shift, coupling constants, and populations in C_6D_6).

Table 4. Limiting Coupling Constants for the Pure *gg*, *gt*, and *tg* Staggered Conformers

$^3J_{H5,H6R}$			$^3J_{H5,H6S}$		
$J_{R,gg}$	$J_{R,gt}$	$J_{R,tg}$	$J_{S,gg}$	$J_{S,gt}$	$J_{S,tg}$
1.0	11.0	4.8	2.2	2.5	10.2

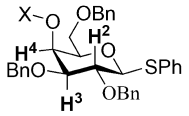
with the aid of eqs 1−3 in the usual manner and reported in Tables 1−3.[47−49] Further inspection of Tables 1−3 reveals that an error of 0.4 Hz in one of the coupling constants results in a maximal change of 5% in the population of any given conformer. Therefore, in the discussion that follows, we adopt 5% as the error limit for any given conformer. In two series of compounds (Tables 2 and 3), small negative populations of the *tg* conformer are computed for some derivatives, which have no physical significance. In view of the 5% error, these negative populations are either indistinguishable from zero or so close to it as not to warrant further discussion.

$$^3J_{5,6R} = {}^3J_{R,gg}f_{gg} + {}^3J_{R,gt}f_{gt} + {}^3J_{R,tg}f_{tg} \quad (1)$$

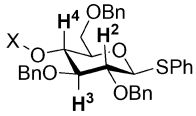
$$^3J_{5,6S} = {}^3J_{S,gg}f_{gg} + {}^3J_{S,gt}f_{gt} + {}^3J_{S,tg}f_{tg} \quad (2)$$

$$1 = f_{gg} + f_{gt} + f_{tg} \quad (3)$$

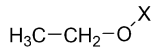
Corrections for the Influence of Electronegative Groups on the Magnitude of Coupling Constants. The derivation of side chain populations from experimental NMR vicinal coupling constants requires that the magnitude of the coupling constants not be affected by differences in electronegativity of the substituents across the series. It is well-known that vicinal coupling constants are reduced by the presence of electronegative substituents in the coupled system,[50−53] but more subtle differences on replacement of ether groups by esters are less appreciated.[51,54,55] Consideration of the $^3J_{3,4}$ coupling constants in the series of gluco- and galactopyranoside derivatives in Figure 4 indicates that replacement of a single ether group in a vicinal diether by an ester results in an increase of approximately 0.5 Hz in the coupling constant, whether the coupled spins have a fixed *trans* or *gauche* relationship irrespective of the solvent, $CDCl_3$ or C_6D_6. However, it is known that in freely rotating systems that more closely approximate the C5−C6 bond in the 6-*O*-substituted series **3** and **28−36** the difference in coupling constants on replacing an ether by an ester substituent is only 0.1 Hz.[54] As this is within the error limit, no correction for the



X:	Bn	Ac	$COCF_3$
$J_{3,4}$ $CDCl_3$:	2.8	nd	3.2
$J_{3,4}$ C_6D_6:	2.8	3.3	3.2
$J_{2,3}$ $CDCl_3$:	9.2	nd	9.1
$J_{2,3}$ C_6D_6:	9.2	9.2	9.1



X:	Bn	Ac	$COCF_3$
$J_{3,4}$ $CDCl_3$:	8.9	9.4	9.6
$J_{3,4}$ C_6D_6:	9.0	9.2	9.5
$J_{2,3}$ $CDCl_3$:	8.8	8.8	8.8
$J_{2,3}$ C_6D_6:	8.7	8.7	8.7



X = Et, $J_{1,2}$ = 7.02
X = Bz, $J_{1,2}$ = 7.14

Figure 4. Differing influences of ether and ester substituents on vicinal coupling constants.

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change in substituents is required for the coupling constants in Table 3.

The influence of replacing an ether substituent by an ester in the β-position to the coupled spins is expected to be smaller, as is borne out by the constant magnitude of the $^3J_{2,3}$ coupling constants in the gluco- and galactopyranosides of Figure 4 regardless of the substituent at the 4-position. The $^3J_{5,6}$ coupling constants in the galactopyranosides **1** and **13**–**22** (Table 1) and the glucopyranosides **2** and **23**–**27** (Table 2) therefore do not require correction for the nature of the substituent at the 4-position.

Comparison of the $^3J_{2,3}$ coupling constants in the galactopyranosides reveals them to be ∼0.4 Hz larger than the corresponding coupling constants in the glucopyranosides (Figure 4), as we have noted previously in a series of rigid bicyclic models.[46] This is a manifestation of the Altona and Haasnoot β-effect wherein the vicinal coupling constant between a pair of coupled antiperiplanar spins is increased by approximately 0.5 Hz when one of the coupled spins is also antiperiplanar to an electron-withdrawing substituent at the β-position.[56] A comparable relationship exists between H^{6R}, H^5, and O4 in the *gt* conformer and between H^{6S}, H^5, and O4 in the *tg* conformer of the galactopyranosides (Figure 5) but not

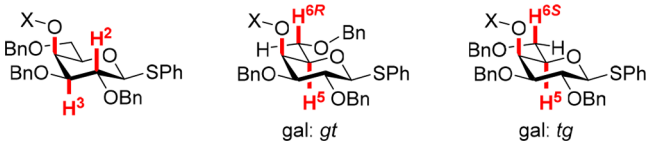

Figure 5. Vicinal coupling constants subject to the Altona–Haasnoot β-effect.

in the glucopyranosides, albeit in a series of rigid bicyclic models, no significant difference was found in the H^5–H^6 coupling constants between the galacto and gluco configurations,[46] suggesting that the effect does not extend to this spin system. Moreover, as the magnitude of the β-effect is not influenced by the switch from an ether to an ester (Figure 4), any residual influence will be of a systematic nature and affect all derivatives to a similar extent. The result of any small systematic β-effect simply will be to overestimate the population of the *gt* and *tg* conformers in the galactopyranoside series (Table 1) and underestimate that of the *gg* conformer correspondingly, with respect to the glucopyranosides (Table 2).

In the final analysis, no corrections to the diagnostic coupling constants used for conformational analysis of the side chain arising from changes in electronegativity of the substituents or the Altona and Haasnoot β-effect were deemed necessary.

Influence of Substituents at the Galactopyranose 4-Position. Comparison of alcohol **1** with ethers **21** and **22** in Table 1 reveals that, while the two ethers have the same population distribution for the side chain given the 5% error, converting the 4-hydroxy group to a benzyl or trifluoroethyl ether has a significant influence on the side chain conformation. Thus, the side chain population of the two ethers of **21** and **22** consists of ∼13% of the *gg* conformer, ∼21% of the *gt* conformer, and ∼66% of the *tg* conformer, whereas the alcohol **1** has a much greater population of the *gg* conformer (∼24%) and a greater population of the *gt* conformer (∼33%), which are balanced by a significantly lower occupancy of the *tg* conformer (∼43%). These differences reflect either the destabilizing influence of the steric bulk at the 4-position on the *gg* conformer or the stabilization of the *gg* conformer in the alcohol **1** by a favorable intramolecular hydrogen bond to O6. Because of the differences in conformation between the alcohol **1** and the ethers **21** and **22** and because glycosyl donors typically do not have unprotected hydroxy groups, we retain the benzyl ether **21** as the standard for further comparisons.

Esterification of **1** gives a series of 4-*O*-esters, alkanoyl **13** and **14**, or aroyl **17**–**20**, that all adopt the same side chain population, but one that differs significantly from that of the benzyl ether **21**. With similar proportions of the *gg* conformer in the ether **21** and the esters **13**, **14**, and **17**–**20**, the change in the overall side chain population can be described as one of an approximately 10% decrease in the population of the *tg* conformer in favor of the *gt* conformer on going from the ethers to the esters. Installation of the more electron-withdrawing trifluoroacetyl and trichloroacetyl groups affords a separate set of two esters **15** and **16**, respectively, whose side chain populations exhibit a pronounced shift away from the *gg* conformer toward the *tg* conformer. This change in population is also accompanied by a reduction in the population of the *gt* conformer with respect to the more standard alkanoyl and aroyl esters such that the *tg* conformer dominates the equilibrium and accounts for ∼74% of the population. Although the effect is smaller, the *p*-nitrobenzoate **20** exhibits a shift in side chain population away from that of the more electron-rich benzoates **17**–**19** in the same direction as that observed with the trifluoro- and trichloroacetates **15** and **16**, suggesting that this change is a function of the electron-withdrawing nature of these esters.

Influence of Substituents at the Glucopyranose 4-Position. In the glucopyranose series, there is also a significant change in the side chain conformation when the alcohol **2** is converted to the benzyl ether **27**. Specifically, benzylation results in a drop in the population of the *tg* conformer that is compensated by an increase in the population of the *gg* conformer and a smaller one in that of the *gt* conformer (Table 2). This effect parallels that seen in the galactopyranose series, in that it is the conformer in which O4 and O6 have a *syn*-pentane-type relationship (*gg* in galactose and *tg* in glucose) whose population is reduced on benzylation (Figure 6), suggesting that this change in conformation is caused by the loss of a favorable hydrogen bond or increased steric interactions in both cases.

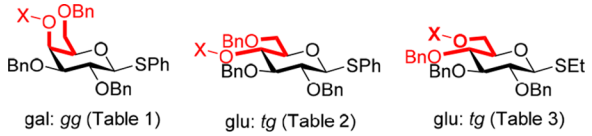

Figure 6. *syn*-Pentane conformations of the galacto- and glucopyranoses destabilized on replacement of a hydroxy group (X = H) by an ether (X = R).

As in the galactopyranose series, we adopt the benzyl ether as the standard for the subsequent comparisons with the influence of alternative protecting groups at the 4-position. The 4-*O*-acetate **23** and the benzoate **25** adopt very similar conformations in which the *gg* conformer is populated to a noticeably lower extent than in the benzyl ether **27**, while the population of the *tg* conformer increases. With the more

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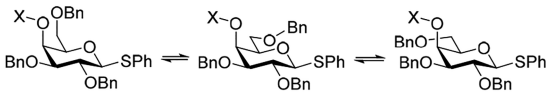
electron-withdrawing trifluoroacetate **24**, the population of the *tg* conformer increases further, but it is balanced by a reduction in the population of both the *gg* and *gt* conformers when compared to the benzyl ether **27**. The population of the side chain conformation of the benzenesulfonate **26** is anomalous insofar as, unlike the other esters, the *tg* conformation is not occupied, presumably for steric reasons arising from an increased *syn*-pentane interaction. This minimal population of the *tg* conformation in **26** results in a higher population of the *gg* conformer than in the acetal and benzoate esters **23** and **25**.

Influence of Substituents at the Glucopyranose 6-Position. In contrast to the differences in side chain population brought about by changing protecting groups at the 4-position in the galacto- and glucopyranose series, changes in the protecting group at the 6-position of the 2,3,4-tri-*O*-benzyl glucopyranosides have a minimal influence on the side chain conformation (Table 3). It is noteworthy, however, that two derivatives, the 6-alcohol **3** and the 6-carbamate **35**, have a small population of the *tg* conformation, with the *syn*-pentane conformation (Figure 6), suggesting that this conformer is stabilized by hydrogen bonding. The only other noteworthy feature from this series of compounds is the increased population of the *gt* conformer at the expense of the *gg* conformer on the installation of the strongly electron-withdrawing trifluoroacetyl group. In view of the relatively small changes in side chain conformation observed in the glucopyranose series with variation in the O6 protecting group, we did not undertake a parallel study in the galactopyranose series.

DISCUSSION

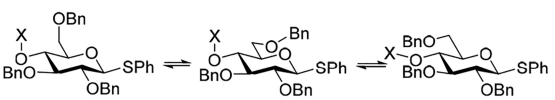
The observed changes in side chain conformation with protecting groups at the 4-position for both the galacto- and glucopyranose systems are summarized in Figure 7. These changes are small, worth <1 kcal·mol^{-1}, difficult to compute accurately with electronic structure calculations,[57−60] and insufficient to account alone for the changes in anomeric reactivity and selectivity seen with such comparable changes in protecting group.[6,61−66] As the effects are small, we make no attempt here to rationalize them in terms of stereoelectronic or other phenomena, other than to note that they are certainly related among other things to the distinct conformational preferences of esters and ethers.[67−69] Nevertheless, such changes can be considered to modulate the larger effects on anomeric reactivity arising from replacing an arming with a disarming protecting group.

a) Galactose



X	*gg*	*gt*	*tg*
Alkyl	13	23	64
Acyl	16	30	54
CF_3CO	8	19	73

b) Glucose



X	*gg*	*gt*	*tg*
Alkyl	57	43	0
Acyl	46	47	7
CF_3CO	58	27	15
$PhSO_2$	55	45	0

Figure 7. Summary of changes in side chain conformation with protecting groups at the 4-position of (a) galactopyranosides and (b) glucopyranosides.

In both the galacto- and glucopyranosyl systems, the replacement of an arming[8] ether protecting group at the 4-position by an ester group results in diminished anomeric reactivity, whether under standard conditions for the activation of thioglycosides[6] or in S_N2-displacements of anomeric bromides by chloride.[9] This change in reactivity is usually understood in terms of the increased electron-withdrawing ability of the ester destabilizing nascent positive or partial positive charge at the reaction center (Scheme 4).[1,5,6,8,17,70] The results presented in Table 1 and summarized in Figure 7a indicate that this effect will be moderated by the change in side chain conformation in the galactopyranoside series. Thus, the increase in the *gt* conformation with its intermediate reactivity at the expense of the less reactive *tg* conformation on replacement of a benzyl ether by an alkanoyl or aroyl ester will partially offset the added electron-withdrawing effect of the ester group. In the glucopyranosyl series on the other hand (Table 2 and Figure 7b), the main effect of the replacement of a benzyl ether by an alkanoyl or aroyl ester is to reduce the population of the most reactive *gg* conformer in favor of population of the least reactive *tg* conformer, thereby complementing the increased electron-withdrawing effect of the ester.

In both the galacto- and glucopyranosyl series (Tables 1 and 2, Figure 7), on replacement of a benzyl ether at the 4-position by the strongly electron-withdrawing trifluoroacetyl group the trichloroacetyl group investigated in the galactose series, Table 1, the population of the most strongly electron-withdrawing *tg* conformer is increased. Thus, in both the galacto- and glucopyranosides, the change in side chain conformation on installation of a trifluoroacetyl group will reinforce the diminution of anomeric reactivity occasioned by the increased electron-withdrawing effect.

The sulfonyl protecting group, initially explored as a strongly electron-withdrawing group at the 2-position capable of stabilizing manno- and rhamnopyranosyl triflates and other sulfonates,[71−73] and subsequently employed with varying degrees of success at the 4-position of 2,6-dideoxyglycopyranosyl donors,[74] and at the 3-, 4-, and 6-positions of other pyranosyl donors,[75,76] does not change the population of the side chain when replacing a benzyl ether at the 4-position of a glucosyl donor (Table 2, Figure 7b). The influence of the 4-*O*-sulfonyl group on glucopyranosylation can therefore be interpreted solely in terms of the change in electron-withdrawing ability.

The small changes in side chain conformation in a series of 4-*O*-alkanoyl and aroyl esters in both the galacto- and glucopyranosyl series do not provide strong support for a protecting-group-induced change in side chain population as the basis for the changes in anomeric selectivity and previously seen in the series of **17**−**20**[77] and related systems,[78] previously explained by the controversial[61−66] concept of stereodirecting

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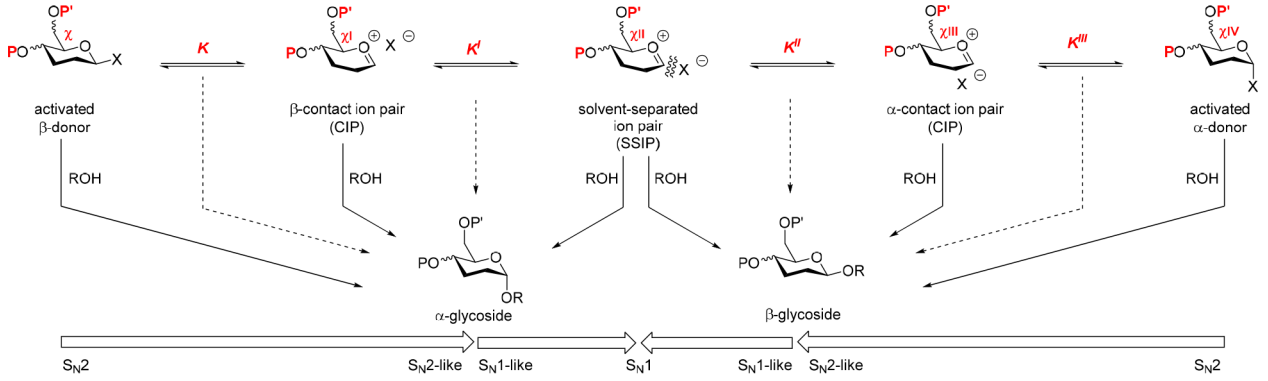
Scheme 4. Abbreviated General Glycosylation Mechanism and Influence of Protecting Groups and Side Chain Conformation



Mechanism = $f(K,K^{I},K^{II},K^{III})$, and K^{I}-K^{III} = f(P, P',χ–χ^{III}) where χ–χ^{III} are the mean side chain conformations in the different intermediates

participation by remote groups. Similarly, the consistent side chain conformation observed with numerous protecting groups at the 6-position in the 2,3,4-tri-*O*-benzyl glucopyranosides (Table 3) does not support a role of the side chain conformation in the changes in anomeric reactivity and glycosylation selectivity reported in such series of compounds.[79−81]

CONCLUSION

Replacement of a benzyl ether at the 4-position of phenyl 2,3,6-tri-*O*-benzyl-*β*-D-thio-galactopyranosides by either an alkanoyl or aroyl ester results in a small but consistent change in the population of the three staggered conformers of the side chain in which the proportion of the less reactive *tg* conformer is reduced in favor of the *gt* conformer. This suggests that the reduction in anomeric reactivity occasioned by the benzyl ether−ester switch seen with glycosyl donors, and attributed to the increased electron-withdrawing ability of the ester, is moderated by a change in side chain conformation in the galactose series. In the corresponding glucopyranosyl series, on the other hand, the same ether−ester change results in an increased population of the less reactive *tg* conformer, indicating that the change in conformation reinforces the effect of the increased electron-withdrawing ability of the ester group. In both the galacto- and glucopyranosyl series, the installation of a trifluoroacetyl group at the 4-position results in an enhanced population of the less reactive *tg* conformer. While the variations in side chain conformation with changes in protecting group recorded here are small, it must be understood that they are for the unactivated glycosyl donor. In view of the partial positive charge on the ring oxygen during glycosylation, it is likely that such changes are accentuated at the transition state for glycosylation reactions.. This possibility is under active investigation in our laboratory.

EXPERIMENTAL SECTION

General Experimental Section. Commercial reagents were used without further purification unless otherwise stated. NMR spectra were recorded in $CDCl_3$ solution unless otherwise stated at 400, 500, or 600 MHz. ^{13}C NMR spectra were recorded in $CDCl_3$ solution unless otherwise stated at 100, 125, or 150 MHz. Mass spectra were recorded in the +ve ion mode using electrospray ionization (ESI-TOF). ESI-HRMS were recorded with a Waters LCT Premier Xe time-of-flight mass spectrometer. Specific rotations were recorded in dichloromethane solution at room temperature.

*Phenyl 2,3,6-Tri-O-benzyl-1-thio-β-D-galactopyranoside (**1**).* Compound **1** was synthesized as described in the literature.[31] ^1H NMR (600 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.42−7.41 (m, 2H), 7.36−7.21 (m, 13H), 7.25−7.23 (m, 3H), 4.83 (d, J = 10.3 Hz, 1H), 4.75 (d, J = 10.3 Hz, 1H), 4.73 (d, J = 11.6 Hz, 1H), 4.69 (d, J = 11.6 Hz, 1H), 4.64 (d, J = 9.9 Hz, 1H), 4.57 (br s, 2H), 4.11 (d, J = 3.2 Hz, 1H), 3.81 (dd, J = 5.7, 10.0 Hz, 1H), 3.78 (dd, J = 5.8, 10.0 Hz, 1H), 3.76 (t, J = 9.5 Hz, 1H), 3.61−3.60 (m, 1H), 3.58 (dd, J = 3.3, 9.5 Hz, 1H), 2.55 (s, 1H). ^1H NMR (600 MHz, C_6D_6) δ 7.68 (dd, J = 8.2, 1.0 Hz, 2H), 7.40 (d, J = 7.6 Hz, 2H), 7.23 (d, J = 7.6 Hz, 2H), 7.17−6.96 (m, 13H), 6.91 (t, J = 7.4 Hz, 1H), 4.85 (d, J = 10.8 Hz, 1H), 4.67 (d, J = 10.8 Hz, 1H), 4.57 (d, J = 9.8 Hz, 1H), 4.34−4.26 (m, 4H), 3.83 (t, J = 9.3 Hz, 1H), 3.79 (d, J = 2.7 Hz, 1H), 3.75 (dd, J = 9.8, 5.8 Hz, 1H), 3.72 (dd, J = 9.8, 6.1 Hz, 1H), 3.25 (t, J = 5.9 Hz, 1H), 3.20 (dd, J = 8.9, 3.2 Hz, 1H), 2.39 (s, 1H). IR (neat) ν 3480 cm^{-1} (O−H).

*Phenyl (6S)-[6-$^2H_1$]-2,3,6-Tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-1**).* Compound **6S-D-1** (0.40 g, 72%) was synthesized from compound **10** analogously to **1**. ^1H NMR (600 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.42−7.40 (m, 2H), 7.36−7.21 (m, 13H), 7.25−7.23 (m, 3H), 4.83 (d, J = 10.3 Hz, 1H), 4.75 (d, J = 10.3 Hz, 1H), 4.73 (d, J = 11.6 Hz, 1H), 4.69 (d, J = 11.6 Hz, 1H), 4.64 (d, J = 9.9 Hz, 1H), 4.56 (br s, 2H), 4.10 (d, J = 3.1 Hz, 1H), 3.76 (d, J = 2.9 Hz, 1H), 3.75 (t, J = 9.5 Hz, 1H), 3.60−3.59 (m, 1H), 3.58 (dd, J = 3.2, 9.3 Hz, 1H). ^1H NMR (600 MHz, C_6D_6) δ 7.69−7.68 (m, 2H), 7.41−7.40 (m, 2H), 7.23−6.89 (m, 16H), 4.84 (d, J = 10.8 Hz, 1H), 4.66 (d, J = 10.8 Hz, 1H), 4.57 (d, J = 9.8 Hz, 1H), 4.31 (d, J = 11.9 Hz, 1H), 4.29−4.27 (m, 3H), 3.82 (t, J = 9.2 Hz, 1H), 3.78 (d, J = 3.1 Hz, 1H), 3.70 (d, J = 6.2 Hz, 1H), 3.23−3.22 (m, 1H), 3.19 (dd, J = 8.9, 3.2 Hz, 1H). HRMS (ESI) m/z calcd for $C_{33}H_{33}DO_5SNa$ $[M + Na]^+$, 566.2087; found, 566.2079.

*Phenyl 2,3,6-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**2**).* Compound **25** (0.01 g, 0.015 mmol) was dissolved in anhydrous methanol (0.5 mL) and cooled to 0 °C before it was treated with Na (catalytic amount). The reaction mixture was stirred under an argon atmosphere at room temperature overnight, quenched with Amberlyst-15 (pH ∼ 4), filtered, and concentrated to dryness. The crude residue was purified by silica gel column chromatography, eluting with hexane/ethyl acetate (19:1 to 4:1) to afford compound **2** (0.005 g, 62%) with spectral data consistent with the literature.[82] ^1H NMR (600 MHz, $CDCl_3$) δ 7.58−7.55 (m, 2H), 7.43−7.24 (m, 18H), 4.92 (d, J = 11.4 Hz, 1H), 4.92 (d, J = 10.2 Hz, 1H), 4.79 (d, J = 11.4 Hz, 1H), 4.75 (d, J = 10.2 Hz, 1H,), 4.70 (d, J = 9.6 Hz, 1H), 4.60 (d, J = 11.9 Hz, 1H), 4.56 (d, J = 11.9 Hz, 1H), 3.80 (dd, J = 10.4, 4.1 Hz, 1H), 3.76 (dd, J = 10.4, 5.3 Hz, 1H), 3.66 (dd, J = 9.6, 8.9 Hz, 1H), 3.54 (dd, J = 8.9, 8.8 Hz, 1H), 3.50 (ddd, J = 9.6, 5.3, 4.1 Hz, 1H), 3.49 (dd, J = 9.6, 8.8 Hz, 1H), 2.54 (br s, 1H). ^1H NMR (600 MHz, C_6D_6) δ 7.69−7.65 (m, 2H), 7.45−7.42 (m, 2H), 7.31−6.94 (m, 16H), 4.94 (d, J = 10.6 Hz, 1H), 4.87 (d, J = 11.7 Hz, 1H), 4.76 (d, J = 11.7 Hz, 1H), 4.69 (d, J = 10.6 Hz, 1H), 4.64 (d, J = 9.7 Hz, 1H), 4.33 (d, J = 11.9 Hz, 1H), 4.30 (d, J = 11.9 Hz, 1H), 3.66 (dd, J = 9.8, 8.9 Hz, 1H), 3.64 (dd, J = 10.4, 3.7 Hz, 1H), 3.60 (dd, J = 10.4, 5.3 Hz, 1H), 3.51 (dd, J = 9.7, 8.7 Hz, 1H), 3.43 (dd, J = 8.9,

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8.7 Hz, 1H), 3.22 (ddd, J = 9.8, 5.3, 3.7 Hz, 1H), 2.23 (s, 1H). IR (neat) ν 3441 cm^{-1} (O−H).

*Phenyl (6S)-[6-$^2H_1$]-2,3,6-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-2**).* Compound **6S-D-2** (0.011 g, 60%) was synthesized from **6S-D-25** (21.7 mg, 0.034 mmol) analogously to **2**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.58−7.53 (m, 1H), 7.44−7.22 (m, 18H), 4.91 (d, J = 11.4 Hz, 1H), 4.91 (d, J = 10.4 Hz, 1H), 4.78 (d, J = 11.4 Hz, 1H), 4.74 (d, J = 10.4 Hz, 1H), 4.69 (d, J = 9.6 Hz, 1H), 4.59 (d, J = 12.0 Hz, 1H), 4.56 (d, J = 12.0 Hz, 1H), 3.74 (d, J = 5.4 Hz, 1H), 3.66 (dd, J = 9.6, 8.8 Hz, 1H), 3.54 (t, J = 8.8 Hz, 1H), 3.48 (dd, J = 9.6, 8.8 Hz, 1H), 3.48 (dd, J = 9.6, 5.4 Hz, 1H), 2.53 (br s, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.71−7.64 (m, 2H), 7.46−7.41 (m, 2H), 7.30−6.93 (m, 16H), 4.94 (d, J = 10.6 Hz, 1H), 4.87 (d, J = 11.7 Hz, 1H), 4.75 (d, J = 11.7 Hz, 1H), 4.69 (d, J = 10.6 Hz, 1H), 4.64 (d, J = 9.7 Hz, 1H), 4.32 (d, J = 12.2 Hz, 1H), 4.30 (d, J = 12.2 Hz, 1H), 3.65 (ddd, J = 9.7, 8.8, 2.9 Hz, 1H), 3.57 (d, J = 5.3 Hz, 1H), 3.51 (dd, J = 9.7, 8.7 Hz, 1H), 3.42 (t, J = 8.8 Hz, 1H), 3.22 (dd, J = 9.7, 5.3 Hz, 1H), 2.19 (d, J = 2.9 Hz, 1H). HRMS (ESI) m/z calcd for $C_{33}H_{33}DO_5SNa$ $[M + Na]^+$, 566.2087; found, 566.2083.

*Ethyl 2,3,4-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**3**).* Compound **3** was synthesized as described in the literature.[33] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.40−7.26 (m, 15H), 4.93 (d, J = 11.0 Hz, 1H), 4.92 (d, J = 10.2 Hz, 1H), 4.87 (d, J = 11.0 Hz, 1H), 4.86 (d, J = 10.9 Hz, 1H), 4.75 (d, J = 10.2 Hz, 1H), 4.66 (d, J = 10.9 Hz, 1H), 4.51 (d, J = 9.9 Hz, 1H), 3.87 (dd, J = 12.2, 2.7 Hz, 1H), 3.71 (dd, J = 9.1, 8.8 Hz, 1H), 3.70 (dd, J = 12.2, 4.8 Hz, 1H), 3.58 (dd, J = 9.6, 9.1 Hz, 1H), 3.41 (dd, J = 9.9, 8.8 Hz, 1H), 3.38 (ddd, J = 9.6, 4.8, 2.7 Hz, 1H), 2.81−2.70 (m, 2H), 1.82 (br s, 1H), 1.33 (t, J = 7.4 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.45−7.42 (m, 2H), 7.35−7.31 (m, 2H), 7.26−7.23 (m, 2H), 7.19−7.05 (m, 9H), 4.99 (d, J = 10.6 Hz, 1H), 4.93 (d, J = 11.2 Hz, 1H), 4.85 (d, J = 11.2 Hz, 1H), 4.83 (d, J = 11.2 Hz, 1H), 4.74 (d, J = 10.6 Hz, 1H), 4.61 (d, J = 11.2 Hz, 1H), 4.36 (d, J = 9.7 Hz, 1H), 3.77−3.71 (m, 1H), 3.66−3.56 (m, 3H), 3.43 (dd, J = 9.7, 8.4 Hz, 1H), 3.13−3.09 (m, 1H), 1.60 (br s, 1H) 2.56−2.42 (m, 2H), 1.11 (t, J = 7.4 Hz, 3H). IR (neat) ν 3484 cm^{-1} (O−H).

*Ethyl (6S)-[6-$^2H_1$]-2,3,4-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-3**).* A solution of compound **12** (0.105 g, 0.27 mmol) in anhydrous methanol (1.0 mL) was cooled to 0 °C, treated with Na (cat), and stirred under an argon atmosphere at room temperature for 1.5 h. Then, the reaction was quenched with Amberlyst-15 resin (pH ∼ 7) and filtered through cotton before it was concentrated to dryness. The crude residue was dissolved in anhydrous pyridine (0.8 mL) and treated with trityl chloride (84 μL, 0.32 mmol) at room temperature. The reaction mixture was stirred in the dark at room temperature for 3 days. The reaction was then quenched with methanol (∼70 μL), stirred for 1 h, and concentrated to dryness. The crude residue was dissolved in chloroform and washed with cold aqueous saturated $NaHCO_3$ and cold brine. The organic layer was dried over anhydrous Na_2SO_4 and concentrated to dryness. The crude residue was dissolved in anhydrous DMF (0.9 mL) and cooled to 0 °C before it was treated with 60% NaH in mineral oil (48 mg, 1.2 mmol) followed by benzyl bromide (141 μL, 1.2 mmol). The reaction mixture was stirred under an argon atmosphere at room temperature for 6 h. The reaction mixture was cooled to 0 °C before it was quenched with water. The aqueous layer was extracted with ethyl acetate. The combined organic layers were washed with brine, dried over anhydrous Na_2SO_4, and concentrated to dryness. The crude residue was passed through a short pad of silica, eluting with hexane/ethyl acetate (7:3), and concentrated. The residue was dissolved in a mixture of glacial acetic acid and water (4:1, 1.3 mL) and heated at 80 °C for 2.5 h. The reaction mixture was concentrated to dryness and purified using silica gel column chromatography, eluting with hexane/ethyl acetate (4:1 to 7:2), obtaining compound **6S-D-3** (0.045 g, 35%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.25 (m, 15H), 4.94 (d, J = 10.9 Hz, 1H), 4.92 (d, J = 10.2 Hz, 1H), 4.87 (d, J = 10.9 Hz, 1H), 4.87 (d, J = 10.9 Hz, 1H), 4.75 (d, J = 10.2 Hz, 1H), 4.66 (d, J = 10.9 Hz, 1H), 4.51 (d, J = 9.8 Hz, 1H), 3.72 (t, J = 9.0 Hz, 1H), 3.68 (d, J = 4.9 Hz, 1H), 3.58 (dd, J = 9.7, 9.0 Hz, 1H), 3.41 (dd, J = 9.8, 8.8 Hz, 1H), 3.38 (dd, J = 9.7, 4.9 Hz, 1H), 2.84−2.69 (m, 2H), 1.33 (t, J = 7.4 Hz, 3H). HRMS (ESI) m/z calcd for $C_{29}H_{33}DO_5SNa$ $[M + Na]^+$, 518.2087; found, 518.2066.

*(6S)-1,6-Anhydro-2,3,4-tri-O-acetyl-6-bromo-β-D-galactopyranose (**5**).* A mixture of l,6-anhydro-2,3,4-tri-*O*-acetyl-β-D-galactopyranose **4**[83] (0.77 g, 2.67 mmol) and *N*-bromosuccinimide (1.9 g, 10.6 mmol)) in trifluorotoluene (40 mL) was refluxed over a 300 W heat lamp for 8 h. After 8 h, the solvent was evaporated under reduced pressure and the crude product dissolved in EtOAc (50 mL). The solution was successively washed with aqueous saturated $Na_2S_2O_3$, aqueous saturated $NaHCO_3$, and dried over Na_2SO_4. Evaporation of the solvent under reduced pressure gave a crude product which was purified through silica gel column chromatography (eluent: 20% EtOAc in hexane) to give **5** (0.73g, 75%) as a yellowish oil. $[\alpha]_D^{22}$ = −63.6 (*c* 1.50, CH_2Cl_2). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.60 (s, 1H), 5.81 (s, 1H), 5.29−5.20 (m, 2H), 4.74 (dd, J = 4.0, 1.3 Hz, 1H), 4.71 (br s, 1H), 2.14 (s, 3H), 2.13 (s, 3H), 2.05 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.2, 169.1, 168.9, 101.7, 82.6, 79.6, 69.3, 66.9, 64.4, 20.7 (2), 20.5. HRMS (ESI) m/z calcd for $C_{12}H_{15}{}^{79}BrO_8Na$ $[M + Na]^+$, 388.9848; found, 388.9849; calcd for $C_{12}H_{15}{}^{81}BrO_8Na$ $[M + Na]^+$, 390.9828; found, 390.9828.

*(6S)-[6-$^2H_1$]-1,6-Anhydro-2,3,4-tri-O-acetyl-β-D-galactopyranose (**6**).* To a solution of **5** (2.3 g, 6.26 mmol) and azobis(isobutyronitrile) (0.1 g, 0.63 mmol) in toluene (170 mL) was added freshly prepared tri-*n*-butyltin deuteride[44] (5.5 g, 18.79 mmol), and the reaction mixture was refluxed for 0.5 h. The cooled reaction mixture was evaporated *in vacuo* to give a crude product which was purified by silica gel column chromatography (eluent: 40% EtOAc in hexane) to give **6** (1.4 g, 77%) as a colorless oil. $[\alpha]_D^{22}$ = −10.0 (*c* 1.15, CH_2Cl_2). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.42 (s, 1H), 5.29−5.20 (m, 2H), 4.75 (s, 1H), 4.45 (d, J = 2.7 Hz, 1H), 4.31 (s, 1H), 2.12 (s, 6H), 2.02 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.5, 169.3, 169.2, 98.9, 72.0, 71.0, 67.4, 64.2 (t, J = 23.5 Hz), 20.8, 20.7, 20.5. HRMS (ESI) m/z calcd for $C_{12}H_{15}DO_8Na$ $[M + Na]^+$, 312.0806; found, 312.0818.

*(6S)-[6-$^2H_1$]-1,2,3,4,6-Penta-O-acetyl-α-D-galactopyranose (**7**).* To a solution of compound **6** (1.4 g, 4.84 mmol) in MeOH (20 mL) was added Na (catalytic amount) slowly and the reaction mixture was stirred for 7 h, then neutralized with Amberlite IR120, filtered, and concentrated under reduced pressure to give (6*S*)-[6-$^2H_1$]-1,6-anhydrogalactose. A solution of (6*S*)-[6-$^2H_1$]-1,6-anhydrogalactose (0.73 g, 4.47 mmol) in Ac_2O (20 mL) was treated with conc. H_2SO_4 (0.35 mL) at 0 °C and stirred for 3 h. The reaction mixture was poured into a saturated aqueous NaOAc solution (50 mL) and extracted with $CHCl_3$ (3 × 20 mL), washed with brine (10 mL), dried over Na_2SO_4, and concentrated under a high vacuum to give the crude product. Column chromatography (eluent: 30% EtOAc in hexane) on silica gel yielded **7** (1.5 g, 81% over two steps) as a colorless syrup with spectral data consistent with the literature.[36] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.29 (d, J = 2.2 Hz, 1H), 5.42 (s, 1H), 5.29−5.19 (m, 2H), 4.27 (d, J = 6.4 Hz, 1H), 3.99 (d, J = 6.5 Hz, 1H), 2.09 (s, 3H), 2.08 (s, 3H), 1.96 (d, J = 2.5 Hz, 3H), 1.95 (d, J = 3.9 Hz, 3H), 1.93 (s, 3H).

*Phenyl (6S)-[6-$^2H_1$]-2,3,4,6-Tetra-O-acetyl-1-thio-β-D-galactopyranoside (**8**).* To a stirred solution of (6*S*)-[6-$^2H_1$]-1,2,3,4,6-penta-*O*-acetyl-α-D-galactopyranose **7** (1.5 g, 3.83 mmol) and thiophenol (047 mL, 4.59 mmol) in CH_2Cl_2 was added $BF_3{\cdot}Et_2O$ (1.9 mL, 7.66 mmol) at 0 °C. The reaction mixture was stirred at room temperature for 22 h, then quenched with aqueous saturated $NaHCO_3$ solution (50 mL) and extracted with CH_2Cl_2 (3 × 25 mL), dried over Na_2SO_4, and concentrated under a high vacuum. The crude product was purified by silica gel column (eluent: 20% EtOAc in hexane) chromatography to give **8**[84] (900 mg, 56%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51−7.48 (m, 2H), 7.30−7.28 (m, 3H), 5.40 (d, J = 2.8 Hz, 1H), 5.22 (t, J = 10.0 Hz, 1H), 5.03 (dd, J = 9.9, 3.3 Hz, 1H), 4.70 (d, J = 10.0 Hz, 1H), 4.17 (d, J = 6.5 Hz, 1H), 3.92 (d, J = 6.8 Hz, 1H), 2.09 (s, 3H), 2.08 (s, 3H), 2.02 (s, 3H), 1.96 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.3, 170.2, 170.0, 169.4, 132.5, 132.4, 128.9, 128.1, 86.6, 74.3, 72.0, 67.2, 61.3 (t, J = 22.2 Hz), 20.8, 20.6, 20.6, 20.6. HRMS (ESI) m/z calcd for $C_{20}H_{23}DO_9SNa$ $[M + Na]^+$, 464.1101; found, 464.1114.

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*Phenyl 2,3-Di-O-benzyl-4,6-O-benzylidene-(6S)-[6-$^2H_1$]-1-thio-β-D-galactopyranoside (**10**).* To a stirred solution of **8** (0.9 g, 2.04 mmol) in MeOH (10.0 mL) was added Na metal (catalytic amount) slowly. The reaction mixture was stirred for 2 h, then neutralized with Amberlite IR120, filtered, and concentrated under reduced pressure to give a crude thiogalactoside. The crude residue was dissolved in dry CH_3CN (30 mL) and treated with benzaldehyde dimethylacetal (0.41 mL, 2.75 mmol) followed by camphorsulfonic acid (4.2 mg, 0.18 mmol) at room temperature. The reaction mixture was stirred for 2.5 h, then neutralized with triethylamine (0.5 mL), and concentrated under reduced pressure to give a crude compound **9**. After filtration through a short silica gel column, compound **9** (0.52 g) was dissolved in dry DMF (10 mL) and then treated with NaH (0.17 g, 4.15 mmol) and BnBr (2.27 g, 1.6 mL, 13.3 mmol) at 0 °C. The resulting solution was warmed to room temperature and stirred for 0.5 h. Upon completion of the reaction (TLC), the excess NaH was quenched using sat. NH_4Cl solution. The product was extracted with EtOAc (3 × 25 mL), and the combined organic layer was washed with brine (10 mL), dried over Na_2SO_4, and concentrated under a high vacuum. The crude product was purified via silica gel column chromatography (30% EtOAc in hexane) to give **10** (0.63 g, 81%) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72−7.71 (m, 2H), 7.55−7.53 (m, 2H), 7.43−7.18 (m, 16H), 5.50 (s, 1H), 4.74−4.68 (m, 4H), 4.62 (d, *J* = 9.5 Hz, 1H), 4.16 (d, *J* = 3.2 Hz, 1H), 3.98 (br s, 1H), 3.91 (t, *J* = 9.4 Hz, 1H), 3.63 (dd, *J* = 9.2, 3.3 Hz, 1H), 3.42 (br s, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 138.6, 138.2, 138.0, 132.9, 132.8, 129.2, 129.0, 128.6, 128.5, 128.4, 128.3, 128.0, 127.9, 127.6, 126.8, 101.5, 86.7, 81.5, 75.6, 75.5, 73.8, 72.0, 69.9, 69.3 (t, *J* = 21.7 Hz). HRMS (ESI) *m*/*z* calcd for $C_{33}H_{31}DO_5SNa$ [M + Na]$^+$, 564.1931; found, 564.1927.

*Ethyl (6S)-[6-$^2H_1$]-2,3,4,6-Tetra-O-acetyl-1-thio-β-D-glucopyranoside (**12**).* Compound **11**[43] (0.1 g, 0.346 mmol) was dissolved in anhydrous dichloroethane (10.5 mL) and treated with (ethylthio)-trimethylsilane (167 μL, 1.03 mmol) followed by ZnI_2 (332 mg, 1.03 mmol). The reaction mixture was stirred under an argon atmosphere at room temperature for 3 h before it was diluted with ethyl acetate and filtered through Celite. The organic layer was washed with aqueous saturated $NaHCO_3$ and brine, dried over anhydrous Na_2SO_4, and concentrated to dryness. The crude residue was dissolved in a mixture of THF:H_2O (1:1, 20 mL), treated with K_2CO_3 (200 mg, 1.44 mmol), and stirred for 15 min. The reaction mixture was then diluted with ethyl acetate, washed with water and brine, and treated with anhydrous Na_2SO_4 before it was concentrated to dryness. Then, the crude residue was passed through a short pad of silica gel, eluting with hexane/ethyl acetate (1:1), and the eluent was concentrated to dryness. The residue (60 mg) was dissolved in pyridine (1.4 mL), treated with acetic anhydride (0.7 mL), and stirred overnight under an argon atmosphere at room temperature. The reaction mixture was then concentrated to dryness, and the crude reaction mixture was purified by silica gel column chromatography, eluting with hexane/ethyl acetate (7:3), to obtain **12** (0.051 g, 40%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.22 (t, *J* = 9.4 Hz, 1H), 5.08 (dd, *J* = 10.0, 9.4 Hz, 1H), 5.03 (dd, *J* = 10.0, 9.4 Hz, 1H), 4.49 (d, *J* = 10.0 Hz, 1H), 4.22 (d, *J* = 5.0 Hz, 1H), 3.70 (dd, *J* = 10.0, 5.0 Hz, 1H), 2.78−2.63 (m, 2H), 2.07 (s, 3H), 2.06 (s, 3H), 2.02 (s, 3H), 2.00 (s, 3H), 1.27 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 170.2, 169.4, 83.5, 75.9, 73.9, 69.8, 68.3, 61.9 (t, *J* = 22.8 Hz), 24.2, 20.7, 20.6, 20.6, 14.8. HRMS (ESI) *m*/*z* calcd for $C_{16}H_{23}DO_9SNa$ [M + Na]$^+$, 416.1102; found, 416.1098.

*Phenyl 4-O-Acetyl-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**13**).*[77] Compound **13** was synthesized as described in the literature.[76] NMR (600 MHz, $CDCl_3$) δ 7.60−7.58 (m, 2H), 7.42−7.40 (m, 2H), 7.37−7.25 (m, 16H), 5.65 (br s, 1H), 4.78 (d, *J* = 11.3 Hz, 1H), 4.77 (d, *J* = 10.3 Hz, 1H), 4.75 (d, *J* = 10.0 Hz, 1H), 4.71−4.67 (m, 1H), 4.57 (d, *J* = 11.7 Hz, 1H), 4.50 (d, *J* = 11.0 Hz, 1H), 4.47 (d, *J* = 11.7 Hz, 1H), 3.77−3.76 (m, 1H), 3.67−3.66 (m, 2H), 3.64 (dd, *J* = 9.5, 6.0 Hz, 1H), 3.55 (dd, *J* = 9.5, 6.7 Hz, 1H), 2.09 (s, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.65−7.61 (m, 2H), 7.39 (t, *J* = 7.6 Hz, 2H), 7.31 (d, *J* = 7.3 Hz, 2H), 7.25 (d, *J* = 7.4 Hz, 2H), 7.17−7.01 (m, 10H), 6.99−6.91 (m, 2H), 5.58 (dd, *J* = 3.3, 1.1 Hz, 1H), 4.80 (d, *J* = 10.7 Hz, 1H), 4.75 (d, *J* = 10.7 Hz, 1H), 4.66 (d, *J* = 11.2 Hz, 1H), 4.56 (d, *J* = 9.7 Hz, 1H), 4.28 (d, *J* = 11.6 Hz, 2H), 4.17 (d, *J* = 11.9 Hz, 1H), 3.80 (t, *J* = 9.5 Hz, 1H), 3.47 (dd, *J* = 9.4, 6.1 Hz, 1H), 3.42 (dd, *J* = 9.4, 6.5 Hz, 1H), 3.33 (dd, *J* = 9.2, 3.3 Hz, 1H), 3.32 (ddd, *J* = 6.5, 6.1, 1.1 Hz, 1H), 1.65 (s, 3H). IR (neat) ν 1742 cm^{-1} (C═O).

*Phenyl 4-O-Acetyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-13**).* Compound **6S-D-13** (0.021 g, 81%) was synthesized from **6S-D-1** analogously to **13**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.60−7.57 (m, 2H), 7.41−7.23 (m, 18H), 5.63 (d, *J* = 1.6 Hz, 1H), 4.79 (d, *J* = 11.1 Hz, 1H), 4.78 (d, *J* = 10.2 Hz, 1H), 4.75 (d, *J* = 10.2 Hz, 1H), 4.72−4.68 (m, 1H), 4.55 (d, *J* = 11.7 Hz, 1H), 4.49 (d, *J* = 11.0 Hz, 1H), 4.45 (d, *J* = 11.7 Hz, 1H), 3.76 (d, *J* = 6.1 Hz, 1H), 3.68−3.66 (m, 2H), 3.61 (d, *J* = 6.0 Hz, 1H), 2.10 (s, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.65−7.62 (m, 2H), 7.40 (d, *J* = 7.6 Hz, 2H), 7.31 (d, *J* = 7.5 Hz, 2H), 7.24 (t, *J* = 10.8 Hz, 2H), 7.18−6.91 (m, 12H), 5.58 (d, *J* = 3.2 Hz, 1H), 4.80 (d, *J* = 10.7 Hz, 1H), 4.75 (d, *J* = 10.7 Hz, 1H), 4.66 (d, *J* = 11.2 Hz, 1H), 4.56 (d, *J* = 9.7 Hz, 1H), 4.28 (d, *J* = 11.4 Hz, 2H), 4.17 (d, *J* = 11.9 Hz, 1H), 3.79 (t, *J* = 9.4 Hz, 1H), 3.47−3.45 (m, 1H), 3.35−3.26 (m, 1H), 1.65 (s, 3H). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{35}DO_6SNa$ [M + Na]$^+$, 608.2193; found, 608.2191.

*Phenyl 2,3,6-Tri-O-benzyl-4-O-pivolyl-1-thio-β-D-galactopyranoside (**14**).*[77] A solution of **1** (0.050 g, 2.77 mmol) in dry pyridine (0.5 mL) was treated with pivaloyl chloride (0.25 mL) at room temperature and stirred at 80 °C for 1 h. The solvents were evaporated under a high vacuum to give a crude residue. The crude product was purified by silica gel column chromatography (eluent: 20% ethyl acetate in hexane) to afford **14** (0.045 g, 78%) as a colorless oil. $[\alpha]_D^{22}$ = +6.6 (*c* 0.50, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.37−7.24 (m, 18H), 5.63 (d, *J* = 2.9 Hz, 1H), 4.73 (d, *J* = 10.6 Hz, 1H), 4.71 (d, *J* = 10.6 Hz, 1H), 4.67 (d, *J* = 10.3 Hz, 1H), 4.63 (d, *J* = 9.5 Hz, 1H), 4.54 (d, *J* = 11.7 Hz, 1H), 4.47 (d, *J* = 11.8 Hz, 1H), 4.45 (d, *J* = 11.0 Hz, 1H), 3.81 (t, *J* = 6.3 Hz, 1H), 3.65 (dd, *J* = 9.2, 3.3 Hz, 1H), 3.62 (dd, *J* = 9.5, 6.1 Hz, 1H), 3.57 (t, *J* = 9.2 Hz, 1H), 3.49 (dd, *J* = 9.5, 6.7 Hz, 1H), 1.14 (s, 9H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 177.4, 138.1, 137.8, 137.6, 133.2, 132.3, 128.8, 128.4, 128.3, 128.2, 128.2, 128.1, 127.9, 127.8, 127.7, 127.6, 127.4, 87.0, 81.4, 76.3, 76.1, 75.6, 73.7, 71.6, 68.2, 66.3, 39.0, 27.1. ^{1}H NMR (600 MHz, C_6D_6) δ 7.66−7.63 (m, 2H), 7.40 (d, *J* = 8.0 Hz, 2H), 7.30−7.24 (m, 4H), 7.18−6.91 (m, 12H), 5.56 (d, *J* = 3.2 Hz, 1H), 4.78 (d, *J* = 10.8 Hz, 1H), 4.76 (d, *J* = 10.9 Hz, 1H), 4.58 (d, *J* = 11.0 Hz, 1H), 4.49 (d, *J* = 9.9 Hz, 1H), 4.30 (d, *J* = 11.9 Hz, 1H), 4.22 (d, *J* = 11.9 Hz, 1H), 4.20 (d, *J* = 11.8 Hz, 1H), 3.69 (t, *J* = 9.4 Hz, 1H), 3.49 (dd, *J* = 9.2, 6.0 Hz, 1H), 3.42 (dd, *J* = 9.2, 6.8 Hz, 1H), 3.37−3.35 (m, 1H), 3.27 (dd, *J* = 9.0, 3.2 Hz, 1H), 1.08 (s, 9H). IR (neat) ν 1732 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{38}H_{42}O_6SNa$ [M + Na]$^+$, 649.2600; found, 649.2584.

*Phenyl 4-O-Pivaloyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-14**).* Compound **6S-D-14** (0.011 g, 90%) was synthesized from **6S-D-1** analogously to **14**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.37−7.23 (m, 18H), 5.63 (d, *J* = 3.1 Hz, 1H), 4.73 (d, *J* = 10.4 Hz, 1H), 4.70 (d, *J* = 10.4 Hz, 1H), 4.66 (d, *J* = 10.3 Hz, 1H), 4.64 (d, *J* = 9.7 Hz, 1H), 4.54 (d, *J* = 11.7 Hz, 1H), 4.48 (d, *J* = 11.8, 1H), 4.44 (d, *J* = 11.0 Hz, 1H), 3.80 (d, *J* = 6.1 Hz, 1H), 3.64 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.60 (d, *J* = 6.1 Hz, 1H), 3.56 (t, *J* = 9.3 Hz, 1H), 1.14 (s, 9H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.66−7.6 (m, 2H), 7.40 (d, *J* = 7.1 Hz, 2H), 7.30−7.25 (m, 4H), 7.17−6.91 (m, 12H), 5.56 (d, *J* = 3.2 Hz, 1H), 4.79 (d, *J* = 10.9 Hz, 1H), 4.76 (d, *J* = 10.9 Hz, 1H), 4.58 (d, *J* = 11.0 Hz, 1H), 4.49 (d, *J* = 9.7 Hz, 1H), 4.30 (d, *J* = 11.9 Hz, 1H), 4.21 (d, *J* = 11.5 Hz, 1H), 4.20 (d, *J* = 11.5 Hz, 1H), 3.70 (t, *J* = 9.4 Hz, 1H), 3.47 (d, *J* = 6.0 Hz, 1H), 3.36 (d, *J* = 5.9 Hz, 1H), 3.27 (dd, *J* = 9.0, 3.3 Hz, 1H), 1.08 (s, 9H). HRMS (ESI) *m*/*z* calcd for $C_{38}H_{41}DO_6SNa$ [M + Na]$^+$, 650.2663; found, 650.2662.

*Phenyl 2,3,6-Tri-O-benzyl-4-O-trifluoroacetyl-1-thio-β-D-galactopyranoside (**15**).*[77] To a stirred solution of **1** (0.05 g, 0.092 mmol) in dry CH_2Cl_2 (1.0 mL) were added pyridine (0.030 mL, 0.18 mmol), trifluoroacetic anhydride (0.026 mL, 0.18 mmol), and DMAP (1.0 mg, 0.009 mmol) at 0 °C. The reaction mixture was stirred for 0.5 h before it was quenched with water (5 mL) and extracted with

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CH_2Cl_2 (3 × 10 mL). The combined extracts were washed with 1 N HCl (5.0 mL) solution, dried over Na_2SO_4, and concentrated under a high vacuum. Silica gel column chromatography (eluent: 10% ethyl acetate in hexane) afforded **15** (0.038 g, 65%) as a colorless oil. $[\alpha]_D^{22}$ = −6.9 (*c* 0.80, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.56−7.52 (m, 2H), 7.37−7.23 (m, 18H), 5.74 (dd, *J* = 3.2, 0.9 Hz, 1H), 4.75 (d, *J* = 11.2 Hz, 1H), 4.68 (d, *J* = 10.2 Hz, 1H), 4.65 (d, *J* = 9.5 Hz, 1H), 4.64 (d, *J* = 9.9 Hz, 1H), 4.52 (d, *J* = 11.3 Hz, 1H), 4.50 (d, *J* = 11.7 Hz, 1H), 4.45 (d, *J* = 11.7 Hz, 1H), 3.82 (ddd, *J* = 8.2, 5.6, 1.0 Hz, 1H), 3.70 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.67 (dd, *J* = 9.3, 5.6 Hz, 1H), 3.61 (t, *J* = 9.5 Hz, 1H), 3.49 (dd, *J* = 9.3, 8.3 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 156.8 (q, *J* = 42.7 Hz, $COCF_3$), 137.9, 137.1, 137.1, 132.8, 132.1, 128.9, 128.5, 128.4, 128.3, 128.2, 128.0, 128.0, 127.9, 127.8, 127.7, 114.5 (q, *J* = 285.8 Hz, CF_3CO), 87.4, 80.5, 76.0, 75.7, 74.7, 73.8, 72.3, 71.3, 67.0. ^{19}F NMR (376 MHz, $CDCl_3$) δ −74.7 ($COCF_3$). ^{1}H NMR (600 MHz, C_6D_6) δ 7.59 (d, *J* = 7.6 Hz, 2H), 7.32 (d, *J* = 7.4 Hz, 2H), 7.19−6.91 (m, 16H), 5.57 (d, *J* = 3.1 Hz, 1H), 4.63 (d, *J* = 10.7 Hz, 1H), 4.53 (d, *J* = 10.8 Hz, 1H), 4.45 (d, *J* = 11.4 Hz, 1H), 4.37 (d, *J* = 9.5 Hz, 1H), 4.19 (d, *J* = 11.4 Hz, 1H), 4.15 (d, *J* = 11.7 Hz, 1H), 4.06 (d, *J* = 11.7 Hz, 1H), 3.71 (t, *J* = 9.4 Hz, 1H), 3.34 (dd, *J* = 9.1, 5.7 Hz, 1H), 3.31 (dd, *J* = 9.1, 8.1 Hz, 1H), 3.24 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.19−3.15 (m, 1H). IR (neat) ν 1790 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{33}O_6F_3SNa$ [M + Na]$^+$, 661.1848; found, 661.1844.

*Phenyl 4-O-Trifluoroacetyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-15**).* Compound **6S-D-15** (0.021 g, 87%) was synthesized from **6S-D-1** analogously to **15**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.56−7. 52 (m, 2H), 7.37−7.24 (m, 18H), 5.74 (d, *J* = 3.0 Hz, 1H), 4.75 (d, *J* = 11.2 Hz, 1H), 4.68 (d, *J* = 10.2 Hz, 1H), 4.65 (d, *J* = 9.5 Hz, 1H), 4.64 (d, *J* = 9.9 Hz, 1H), 4.52 (d, *J* = 11.6 Hz, 1H), 4.50 (d, *J* = 11.6 Hz, 1H), 4.45 (d, *J* = 11.6 Hz, 1H), 3.81 (d, *J* = 5.6 Hz, 1H), 3.70 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.65 (d, *J* = 5.6 Hz, 1H), 3.61 (t, *J* = 9.4 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.61−7.58 (m, 2H), 7.33 (d, *J* = 7.2 Hz, 2H), 7.21−6.92 (m, 16H), 5.58 (d, *J* = 3.0 Hz, 1H), 4.63 (d, *J* = 10.8 Hz, 1H), 4.53 (d, *J* = 10.8 Hz, 1H), 4.45 (d, *J* = 11.4 Hz, 1H), 4.38 (d, *J* = 9.7 Hz, 1H), 4.19 (d, *J* = 11.4 Hz, 1H), 4.16 (d, *J* = 11.8 Hz, 1H), 4.06 (d, *J* = 11.8 Hz, 1H), 3.71 (t, *J* = 9.4 Hz, 1H), 3.32 (d, *J* = 5.6 Hz, 1H), 3.25 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.17 (d, *J* = 5.7 Hz, 1H). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{32}F_3DO_6SNa$ [M + Na]$^+$, 662.1910; found, 662.1905.

*Phenyl 2,3,6-Tri-O-benzyl-4-O-trichloroacetyl-1-thio-β-D-galactopyranoside (**16**).*[77] Compound **16** (0.058 g, 92%) was synthesized from **1** analogously to **15**, as a colorless oil. $[\alpha]_D^{22}$ = −8.0 (*c* 1.80, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.59−7.52 (m, 2H), 7.39−7.21 (m, 18H), 5.71 (d, *J* = 2.9 Hz, 1H), 4.80 (d, *J* = 11.4 Hz, 1H), 4.65 (d, *J* = 10.6 Hz, 1H), 4.64 (d, *J* = 9.9 Hz, 1H), 4.62 (d, *J* = 10.3 Hz, 1H), 4.54 (d, *J* = 11.6 Hz, 1H), 4.51 (d, *J* = 11.4 Hz, 1H), 4.49 (d, *J* = 11.4 Hz, 1H), 3.87 (dd, *J* = 7.9, 6.0 Hz, 1H), 3.74−3.72 (m, 1H), 3.71 (dd, *J* = 9.2, 5.7 Hz, 1H), 3.68 (t, *J* = 9.3 Hz, 1H), 3.59 (dd, *J* = 9.2, 8.2 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 161.3, 137.9, 137.3, 137.3, 132.6, 132.3, 129.0, 128.6, 128.3, 128.3, 128.1, 128.0, 127.9, 127.8, 127.6, 89.9, 87.1, 80.9, 75.6, 75.6, 75.2, 73.9, 72.2, 72.1, 67.3. ^{1}H NMR (600 MHz, C_6D_6) δ 7.62−7.60 (m, 2H), 7.33 (d, *J* = 7.4 Hz, 2H), 7.24−7.19 (m, 4H), 7.16−7.07 (m, 11H), 6.95−6.91 (m, 1H), 5.53 (d, *J* = 3.0 Hz, 1H), 4.69 (d, *J* = 10.8 Hz, 1H), 4.66 (d, *J* = 10.8 Hz, 1H), 4.52 (d, *J* = 11.4 Hz, 1H), 4.38 (d, *J* = 9.9 Hz, 1H), 4.23 (d, *J* = 11.7 Hz, 1H), 4.19 (d, *J* = 11.4 Hz, 1H), 4.18 (d, *J* = 11.7 Hz, 1H), 3.79 (t, *J* = 9.4 Hz, 1H), 3.46 (m, 1H), 3.43 (m, 1H), 3.29−3.28 (m, 1H), 3.28−3.25 (m, 1H). IR (neat) ν 1769 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{33}O_6Cl_3SNa$ [M + Na]$^+$, 709.0961; found, 709.0955.

*Phenyl 4-O-Trichloroacetyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-16**).* Compound **6S-D-16** (0.029 g, 90%) was synthesized from **6S-D-1** analogously to **1**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.59−7.52 (m, 2H), 7.39−7.21 (m, 18H), 5.70 (d, *J* = 2.9 Hz, 1H), 4.79 (d, *J* = 11.2 Hz, 1H), 4.65 (d, *J* = 10.9 Hz, 1H), 4.63 (d, *J* = 9.9 Hz, 1H), 4.62 (d, *J* = 10.6 Hz, 1H), 4.53 (t, *J* = 11.6 Hz, 1H), 4.52 (d, *J* = 11.6 Hz, 1H), 4.49 (d, *J* = 11.4 Hz, 1H), 3.86 (d, *J* = 5.7 Hz, 1H), 3.72 (dd, *J* = 9.1, 3.0 Hz, 1H), 3.69 (d, *J* = 5.7, 1H), 3.68 (t, *J* = 9.3 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.63−7.59 (m, 2H), 7.33 (d, *J* = 7.4 Hz, 2H), 7.23−7.20 (m, 4H), 7.17−6.90 (m, 12H), 5.53 (d, *J* = 3.0 Hz, 1H), 4.69 (d, *J* = 10.8 Hz, 1H), 4.66 (d, *J* = 10.8 Hz, 1H), 4.52 (d, *J* = 11.3 Hz, 1H), 4.39 (d, *J* = 9.7 Hz, 1H), 4.22 (d, *J* = 11.7 Hz, 1H), 4.19 (d, *J* = 11.4 Hz, 1H), 4.17 (d, *J* = 11.8 Hz, 1H), 3.79 (t, *J* = 9.4 Hz, 1H), 3.43 (d, *J* = 5.7 Hz, 1H), 3.29−3.26 (m, 2H). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{32}Cl_3DO_6SNa$ [M + Na]$^+$, 710.1024; found, 710.1016.

*Phenyl 4-O-Benzoyl-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**17**).*[77] Compound **17** was synthesized as described in the literature.[76] ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.01−7.93 (m, 2H), 7.66−7.65 (m, 2H), 7.61−7.59 (m, 1H), 7.47−7.45 (m, 2H), 7.40−7.39 (m, 2H), 7.35−7.22 (m, 16H), 5.91 (d, *J* = 3.0 Hz 1H), 4.87 (d, *J* = 11.4 Hz, 1H), 4.74 (br s, 2H), 4.70 (d, *J* = 9.5 Hz, 1H), 4.54 (d, *J* = 11.0 Hz, 1H), 4.52 (dd, *J* = 10.6 Hz, 1H), 4.46 (d, *J* = 10.6 Hz, 1H), 3.92−3.89 (m, 1H), 3.77 (d, *J* = 9.2, 3.3 Hz, 1H), 3.72 (t, *J* = 9.4 Hz, 1H), 3.69 (dd, *J* = 9.6, 5.8 Hz, 1H), 3.59 (dd, *J* = 9.6, 6.8 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.11 (d, *J* = 8.1 Hz, 2H), 7.70 (dd, *J* = 12.2, 5.2 Hz, 2H), 7.39 (d, *J* = 7.9 Hz, 2H), 7.26 (d, *J* = 7.9 Hz, 2H), 7.20 (d, *J* = 7.9 Hz, 2H), 7.17−6.95 (m, 15H), 5.87 (d, *J* = 3.1 Hz, 1H), 4.75 (d, *J* = 11.4 Hz, 1H), 4.72 (d, *J* = 10.9 Hz, 1H), 4.67 (d, *J* = 10.9 Hz, 1H), 4.54 (d, *J* = 9.7 Hz, 1H), 4.31 (d, *J* = 11.4 Hz, 1H), 4.19 (d, *J* = 11.8 Hz, 1H), 4.12 (d, *J* = 11.9 Hz, 1H), 3.83 (t, *J* = 9.4 Hz, 1H), 3.53 (dd, *J* = 9.3, 6.1 Hz, 1H), 3.49 (dd, *J* = 9.3, 6.6 Hz, 1H), 3.42 (t, *J* = 4.8 Hz, 1H), 3.42−3.40 (m, 1H). IR (neat) ν 1722 cm^{-1} (C═O).

*Phenyl 4-O-Benzoyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-17**).* Compound **6S-D-17** (0.021 g, 84%) was synthesized analogously as **17** from **6S-D-1**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.02−7.99 (m, 2H), 7.67−7.64 (m, 2H), 7.61−7.59 (m, 1H), 7.47−7.45 (m, 2H), 7.40−7.39 (m, 2H), 7.37−7.21 (m, 16H), 5.91 (d, *J* = 3.1 Hz, 1H), 4.87 (d, *J* = 11.2 Hz, 1H), 4.74 (br s, 2H), 4.71 (d, *J* = 9.5 Hz, 1H), 4.54 (d, *J* = 11.2 Hz, 1H), 4.52 (d, *J* = 11.8 Hz, 1H), 4.46 (d, *J* = 11.8 Hz, 1H), 3.90 (d, *J* = 6.0 Hz, 1H), 3.77 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.72 (t, *J* = 9.3 Hz, 1H), 3.69 (d, *J* = 6.0 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.11 (d, *J* = 7.7 Hz, 2H), 7.70 (d, *J* = 7.3 Hz, 2H), 7.39 (d, *J* = 7.5 Hz, 2H), 7.26 (d, *J* = 7.4 Hz, 2H), 7.20 (d, *J* = 7.5 Hz, 2H), 7.14 (t, *J* = 7.6 Hz, 2H), 7.09−6.94 (m, 13H), 5.87 (d, *J* = 3.1 Hz, 1H), 4.75 (d, *J* = 11.4 Hz, 1H), 4.72 (d, *J* = 10.9 Hz, 1H), 4.67 (d, *J* = 10.9 Hz, 1H), 4.54 (d, *J* = 9.7 Hz, 1H), 4.31 (d, *J* = 11.4 Hz, 1H), 4.19 (d, *J* = 11.9 Hz, 1H), 4.12 (d, *J* = 11.9 Hz, 1H), 3.83 (t, *J* = 9.4 Hz, 1H), 3.51 (d, *J* = 6.0 Hz, 1H), 3.42−3.40 (m, 2H). HRMS (ESI) *m*/*z* calcd for $C_{40}H_{37}DO_6SNa$ [M + Na]$^+$, 670.2350; found, 670.2344.

*Phenyl 4-O-(p-Methylbenzoyl)-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**18**).*[77] Compound **18** (0.057 g, 95%) was synthesized from **1** analogously to **19**, as a colorless oil. $[\alpha]_D^{22}$ = +20.9 (*c* 0.55, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.89−7.88 (m, 2H), 7.64−7.63 (m, 2H), 7.38−7.21 (m, 20H), 5.87 (d, *J* = 3.0 Hz, 1H), 4.84 (d, *J* = 11.2 Hz, 1H), 4.71 (br s, 2H), 4.69 (d, *J* = 9.5 Hz, 1H), 4.53 (d, *J* = 11.0 Hz, 1H), 4.51 (d, *J* = 11.7 Hz, 1H), 4.45 (d, *J* = 11.7 Hz, 1H), 3.89−3.87 (m, 1H), 3.74 (dd, *J* = 9.1, 3.2 Hz, 1H), 3.69 (t, *J* = 9.2 Hz, 1H), 3.68 (dd, *J* = 9.5, 5.9 Hz, 1H), 3.57 (dd, *J* = 9.5, 6.8 Hz, 1H), 2.44 (s, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 165.7, 143.9, 138.3, 137.6, 132.9, 132.8, 130.0, 129.1, 128.8, 128.4, 128.3, 128.3, 128.2, 128.2, 127.9, 127.7, 127.7, 127.6, 127.0, 87.1, 81.4, 76.5, 76.4, 75.7, 73.7, 71.7, 68.5, 67.1, 21.7. ^{1}H NMR (600 MHz, C_6D_6) δ 8.09 (d, *J* = 8.0 Hz, 2H), 7.74−7.70 (m, 2H), 7.39 (d, *J* = 7.6 Hz, 2H), 7.28 (d, *J* = 7.6 Hz, 2H), 7.21 (t, *J* = 8.6 Hz, 2H), 7.15 (dd, *J* = 15.7, 8.0 Hz, 2H), 7.12−6.95 (m, 10H), 6.84 (d, *J* = 8.0 Hz, 2H), 5.88 (d, *J* = 3.2 Hz, 1H), 4.77 (d, *J* = 11.4 Hz, 1H), 4.73 (d, *J* = 10.9 Hz, 1H), 4.67 (d, *J* = 10.9 Hz, 1H), 4.55 (d, *J* = 9.7 Hz, 1H), 4.32 (d, *J* = 11.8 Hz, 1H), 4.20 (d, *J* = 11.8 Hz, 1H), 4.14 (d, *J* = 10.8 Hz, 1H), 3.86 (t, *J* = 9.4 Hz, 1H), 3.56 (dd, *J* = 9.4, 6.2, Hz, 1H), 3.52 (dd, *J* = 9.4, 6.5 Hz, 1H), 3.45−3.43 (m, 1H), 3.42−3.41 (m, 1H) 1.90 (s, 3H). IR (neat) ν 1720 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{41}H_{40}O_6SNa$ [M + Na]$^+$, 683.2443; found, 683.2446.

*Phenyl 4-O-(p-Methylbenzoyl)-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-18**).* Compound **6S-D-18** (0.016 g, 65%) was synthesized from **6S-D-1** analogously to **18**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.88 (d, *J* = 8.1 Hz, 2H), 7.64−7.63 (m, 2H),

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7.39−7.19 (m, 20H), 5.86 (d, J = 3.0 Hz, 1H), 4.83 (d, J = 11.1 Hz, 1H), 4.70 (br s, 2H), 4.68 (d, J = 9.5 Hz, 1H), 4.50 (d, J = 11.1 Hz, 1H), 4.49 (d, J = 11.8 Hz, 1H), 4.43 (d, J = 11.8 Hz, 1H), 3.87 (d, J = 5.9 Hz, 1H), 3.74 (dd, J = 9.1, 3.2 Hz, 1H), 3.68 (t, J = 9.3 Hz, 1H), 3.66 (d, J = 6.0 Hz, 1H), 2.44 (s, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.09 (d, J = 8.2 Hz, 2H), 7.75−7.67 (m, 2H), 7.39 (d, J = 7.2 Hz, 2H), 7.28 (d, J = 7.2 Hz, 2H), 7.22 (d, J = 7.2 Hz, 1H), 7.14 (t, J = 7.6 Hz, 2H), 7.11−6.95 (m, 10H), 6.84 (d, J = 8.1 Hz, 2H), 5.88 (d, J = 3.1 Hz, 1H), 4.77 (d, J = 11.4 Hz, 1H), 4.73 (d, J = 10.9 Hz, 1H), 4.67 (d, J = 10.8 Hz, 1H), 4.55 (d, J = 9.7 Hz, 1H), 4.32 (d, J = 11.4 Hz, 1H), 4.19 (d, J = 11.9 Hz, 1H), 4.14 (d, J = 11.9 Hz, 1H), 3.87 (t, J = 9.4 Hz, 1H), 3.54 (d, J = 6.2 Hz, 1H), 3.44−3.41 (m, 2H), 1.90 (s, 3H). HRMS (ESI) m/z calcd for $C_{41}H_{39}DO_6SNa$ $[M + Na]^+$, 684.2506; found, 684.2499.

*Phenyl 4-O-(p-Methoxybenzoyl)-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**19**).*[77] To a stirred solution of **1** (0.050 g, 0.092 mmol) in dry pyridine (1.0 mL) was added 4-methoxy benzoyl chloride (0.025 mL, 0.184 mmol) and DMAP (1.0 mg, 0.009 mmol) at room temperature. The reaction mixture was stirred for 8 h before the solvents were evaporated under a high vacuum to give a crude product, which was dissolved in CH_2Cl_2 (10 mL) and washed with 1 N HCl (5 mL) solution, followed by sat. $NaHCO_3$ solution, dried over Na_2SO_4, and concentrated under a high vacuum. Silica gel column chromatography (eluent: 20% ethyl acetate in hexane) afforded **19**[61] (0.050 g, 80%) as a colorless oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.97−7.95 (m, 2H), 7.66−7.62 (m, 2H), 7.40−7.39 (m, 2H), 7.36−7.20 (m, 16H), 6.94−6.92 (m, 2H), 5.87 (d, J = 3.0 Hz, 1H), 4.86 (d, J = 11.4 Hz, 1H), 4.74 (br s, 2H), 4.71 (d, J = 9.2 Hz, 1H), 4.53 (d, J = 11.0, 1H), 4.50 (d, J = 11.7 Hz, 1H), 4.46 (d, J = 11.7 Hz, 1H), 3.89 (s, 3H), 3.89−3.87 (m, 1H), 3.75 (dd, J = 9.2, 2.9 Hz, 1H), 3.71 (t, J = 9.2 Hz, 1H), 3.69 (dd, J = 9.6, 6.1 Hz, 1H), 3.59 (dd, J = 9.6, 6.5 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.11 (d, J = 8.7 Hz, 2H), 7.71 (d, J = 7.4 Hz, 2H), 7.40 (d, J = 7.4 Hz, 2H), 7.29 (d, J = 7.4 Hz, 2H), 7.23 (d, J = 7.3 Hz, 2H), 7.17−6.93 (m, 12H), 6.56 (d, J = 8.8 Hz, 2H), 5.88 (d, J = 3.0 Hz, 1H), 4.79 (d, J = 11.4 Hz, 1H), 4.76 (d, J = 10.8 Hz, 1H), 4.71 (d, J = 10.8 Hz, 1H), 4.57 (d, J = 9.7 Hz, 1H), 4.33 (d, J = 11.4 Hz, 1H), 4.21 (d, J = 11.9 Hz, 1H), 4.15 (d, J = 11.8 Hz, 1H), 3.87 (t, J = 9.4 Hz, 1H), 3.57 (dd, J = 9.4, 6.2 Hz, 1H), 3.54 (dd, J = 9.4, 6.4 Hz, 1H), 3.47−3.41 (m, 2H), 3.08 (s, 3H). IR (neat) ν 1728 cm^{-1} (C═O).

*Phenyl 4-O-(p-Methoxybenzoyl)-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-19**).* Compound **6S-D-19** (0.009 g, 71%) was synthesized from **6S-D-1** analogously to **19**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.98−7.91 (m, 2H), 7.69−7.58 (m, 2H), 7.39−7.18 (m, 18H), 6.91 (d, J = 8.9 Hz, 2H), 5.85 (d, J = 3.1 Hz, 1H), 4.83 (d, J = 11.2 Hz, 1H), 4.72 (br s, 2H), 4.68 (d, J = 9.5 Hz, 1H), 4.51 (d, J = 11.6 Hz), 4.49 (d, J = 11.6 Hz, 1H), 4.44 (d, J = 11.7 Hz, 1H), 3.89 (s, 3H), 3.87−3.85 (m, 1H), 3.73 (dd, J = 9.2, 3.2 Hz, 1H), 3.69 (t, J = 9.3 Hz, 1H), 3.66 (d, J = 6.2 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.11 (d, J = 8.8 Hz, 2H), 7.71 (d, J = 7.3 Hz, 2H), 7.40 (d, J = 7.5 Hz, 2H), 7.29 (d, J = 7.4 Hz, 2H), 7.23 (d, J = 7.3 Hz, 2H), 7.17−6.93 (m, 12H), 6.55 (d, J = 8.8 Hz, 2H), 5.88 (d, J = 3.1 Hz, 1H), 4.79 (d, J = 11.4 Hz, 1H), 4.76 (d, J = 10.8 Hz, 1H), 4.71 (d, J = 10.8 Hz, 1H), 4.57 (d, J = 9.7 Hz, 1H), 4.33 (d, J = 11.4 Hz, 1H), 4.21 (d, J = 11.9 Hz, 1H), 4.15 (d, J = 11.9 Hz, 1H), 3.87 (t, J = 9.4 Hz, 1H), 3.55 (d, J = 6.1 Hz, 1H), 3.45−3.41 (m, 2H), 3.08 (s, 3H). HRMS (ESI) m/z calcd for $C_{41}H_{39}DO_7SNa$ $[M + Na]^+$, 700.2455; found, 700.2449.

*Phenyl 4-O-(p-Nitrobenzoyl)-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**20**).*[77] Compound **20** (0.053 g, 84%) was synthesized from **1** analogously to **19**, as a colorless oil. $[\alpha]_D^{22}$ = +19.5 (c 1.95, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.26−8.24 (m, 2H), 8.07−8.06 (m, 2H), 7.65−7.63 (m, 2H), 7.39−7.19 (m, 18H), 5.90 (d, J = 2.3 Hz, 1H), 4.83 (d, J = 10.6 Hz, 1H), 4.78 (d, J = 10.3 Hz, 1H), 4.73 (d, J = 10.3 Hz, 1H), 4.70 (d, J = 9.5 Hz, 1H), 4.54 (d, J = 11.0 Hz, 1H), 4.52 (d, J = 11.7 Hz, 1H), 4.43 (d, J = 11.7 Hz, 1H), 3.91 (t, J = 6.1 Hz, 1H), 3.78 (dd, J = 9.2, 3.3 Hz, 1H), 3.69 (dd, J = 9.5, 5.7 Hz, 1H), 3.64 (t, J = 9.4 Hz, 1H), 3.56 (dd, J = 9.5, 7.2 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 163.8, 150.6, 138.1, 137.3, 137.3, 135.1, 133.3, 132.5, 130.9, 128.8, 128.4, 128.2, 128.1, 127.9, 127.9, 127.9, 127.8, 123.5, 87.1, 81.3, 76.5, 75.8, 75.7, 73.7, 72.1, 68.5, 67.9. ^{1}H NMR (600 MHz, C_6D_6) δ 7.70−7.65 (m, 4H), 7.59−7.55 (m, 2H), 7.41 (d, J = 7.3 Hz, 2H), 7.25 (d, J = 7.2 Hz, 2H), 7.15 (dd, J = 16.1, 7.8 Hz, 4H), 7.08−6.91 (m, 10H), 5.79 (d, J = 3.1 Hz, 1H), 4.85 (d, J = 10.7 Hz, 1H), 4.77 (d, J = 10.8 Hz, 1H), 4.67 (d, J = 11.1 Hz, 1H), 4.52 (d, J = 9.7 Hz, 1H), 4.28 (d, J = 11.0 Hz, 1H), 4.24 (d, J = 11.0 Hz, 1H), 4.13 (d, J = 11.9 Hz, 1H), 3.73 (t, J = 9.3 Hz, 1H), 3.47 (dd, J = 8.9, 5.6 Hz, 1H), 3.42 (dd, J = 8.9, 7.0 Hz, 1H), 3.41−3.39 (m, 1H), 3.38−3.37 (m, 1H). IR (neat) ν 1729 cm^{-1} (C═O). HRMS (ESI) m/z calcd for $C_{40}H_{37}NO_8SNa$ $[M + Na]^+$, 714.2138; found, 714.2120.

*Phenyl 4-O-(p-Nitrobenzoyl)-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-20**).* Compound **6S-D-20** (0.010 g, 83%) was synthesized from **6S-D-1** analogously to **20**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.26−8.24 (m, 2H), 8.07−8.06 (m, 2H), 7.65−7.64 (m, 2H), 7.44−7.18 (m, 18H), 5.90 (d, J = 3.1 Hz, 1H), 4.83 (d, J = 11.0 Hz, 1H), 4.78 (d, J = 10.8 Hz, 1H), 4.73 (d, J = 10.3 Hz, 1H), 4.70 (d, J = 9.7 Hz, 1H), 4.54 (d, J = 11.0 Hz, 1H), 4.52 (d, J = 11.7 Hz, 1H), 4.43 (d, J = 11.8 Hz, 1H), 3.91 (d, J = 5.7 Hz, 1H), 3.78 (dd, J = 9.1, 3.1 Hz, 1H), 3.67 (d, J = 5.7 Hz, 1H), 3.64 (t, J = 9.4 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.69−7.65 (m, 4H), 7.59−7.55 (m, 2H), 7.41 (d, J = 7.3 Hz, 2H), 7.25 (d, J = 7.3 Hz, 2H), 7.18−6.90 (m, 14H), 5.78 (d, J = 3.1 Hz, 1H), 4.85 (d, J = 10.7 Hz, 1H), 4.77 (d, J = 10.8 Hz, 1H), 4.67 (d, J = 11.1 Hz, 1H), 4.51 (d, J = 9.7 Hz, 1H), 4.28 (d, J = 11.1 Hz, 1H), 4.24 (d, J = 12.0 Hz, 1H), 4.12 (d, J = 11.9 Hz, 1H), 3.72 (t, J = 9.4 Hz, 1H), 3.45 (d, J = 5.7 Hz, 1H, H), 3.40−3.35 (m, 2H). HRMS (ESI) m/z calcd for $C_{40}H_{36}NDO_8SNa$ $[M + Na]^+$, 715.2200; found, 715.2206.

*Phenyl 2,3,4,6-Tetra-O-benzyl-1-thio-β-D-galactopyranoside (**21**).* Compound **21** was synthesized as described in the literature.[85] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.58−7.56 (m, 2H), 7.39−7.27 (m, 21H), 7.20−7.18 (m, 2H), 4.98 (d, J = 11.7 Hz, 1H), 4.79 (d, J = 10.3 Hz, 1H), 4.75 (d, J = 11.7 Hz, 1H), 4.74−4.73 (m, 1H), 4.73 (d, J = 11.7 Hz, 1H), 4.65 (d, J = 9.9 Hz, 1H), 4.61 (d, J = 11.7 Hz, 1H), 4.47 (d, J = 11.7 Hz, 1H), 4.43 (d, J = 11.7 Hz, 1H), 3.99 (dd, J = 2.8, 1.0 Hz, 1H), 3.95 (t, J = 9.5 Hz, 1H), 3.67 (m, 1H), 3.65 (m, 1H), 3.63−3.62 (m, 1H), 3.61 (dd, J = 2.8, 9.2 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.70−7.67 (m, 2H), 7.37 (d, J = 7.2 Hz, 2H), 7.30 (d, J = 7.2 Hz, 2H), 7.21 (d, J = 7.2 Hz, 2H), 7.18 (d, J = 7.1 Hz, 2H), 7.14−7.09 (m, 8H), 7.05 (dt, J = 14.7, 7.4 Hz, 4H), 6.99−6.89 (m, 3H), 4.95 (d, J = 11.4 Hz, 1H), 4.79 (d, J = 10.7 Hz, 1H), 4.64 (d, J = 10.8 Hz, 1H), 4.59 (d, J = 9.6 Hz, 1H), 4.52 (d, J = 11.4 Hz, 1H), 4.42 (d, J = 11.9 Hz, 1H), 4.37 (d, J = 11.9 Hz, 1H), 4.22 (d, J = 11.8 Hz, 1H), 4.16 (d, J = 11.8 Hz, 1H), 4.11 (t, J = 9.4 Hz, 1H), 3.78 (dd, J = 2.9, 1.1 Hz, 1H), 3.66 (dd, J = 9.1, 7.4 Hz, 1H), 3.57 (dd, J = 9.1, 5.7 Hz, 1H), 3.32 (ddd, J = 7.3, 5.7, 1.0 Hz, 1H), 3.29 (dd, J = 9.2, 2.8 Hz, 1H).

*Phenyl (6S)-[6-$^2H_1$]-2,3,4,6-Tetra-O-benzyl-1-thio-β-D-galactopyranoside (**6S-D-21**).* Compound **6S-D-21** (0.012 g, 70%) was synthesized from **6S-D-1** analogously to **21**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.58−7.56 (m, 2H), 7.40−7.26 (m, 21H), 7.21−7.16 (m, 2H), 4.97 (d, J = 11.5 Hz, 1H), 4.79 (d, J = 10.2 Hz, 1H), 4.75 (d, J = 11.7 Hz, 1H), 4.74−4.73 (m, 1H), 4.72 (d, J = 11.7 Hz, 1H), 4.65 (d, J = 9.7 Hz, 1H), 4.61 (d, J = 11.5 Hz, 1H), 4.48 (d, J = 11.7 Hz, 1H), 4.42 (d, J = 11.7 Hz, 1H), 3.99 (d, J = 2.6 Hz, 1H), 3.94 (t, J = 9.5 Hz, 1H), 3.65 (d, J = 5.8 Hz, 1H, H), 3.62−3.61 (m, 2H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.70−7.67 (m, 2H), 7.37 (d, J = 7.6 Hz, 2H), 7.30 (d, J = 7.5 Hz, 2H), 7.21−7.16 (m, 4H), 7.15−7.02 (m, 12H), 6.99−6.89 (m, 3H), 4.95 (d, J = 11.4 Hz, 1H), 4.79 (d, J = 10.7 Hz, 1H), 4.64 (d, J = 10.8 Hz, 1H), 4.59 (d, J = 9.6 Hz, 1H), 4.52 (d, J = 11.4 Hz, 1H), 4.42 (d, J = 11.9 Hz, 1H), 4.37 (d, J = 11.9 Hz, 1H), 4.22 (d, J = 11.9 Hz, 1H), 4.16 (d, J = 11.8 Hz, 1H), 4.11 (t, J = 9.4 Hz, 1H), 3.78 (d, J = 2.6 Hz, 1H), 3.55 (d, J = 5.6 Hz, 1H), 3.33−3.26 (m, 2H). HRMS (ESI) m/z calcd for $C_{40}H_{39}DO_5SNa$ $[M + Na]^+$, 656.2557; found, 656.2548.

*Phenyl 2,3,6-Tri-O-benzyl-4-O-(1′,1′,1′-trifluoroethyl)-1-thio-β-D-galactopyranoside (**22**).*[77] To a solution of phenyl 2,3,6-tri-*O*-benzyl-1-thio-D-glucopyranoside (**2**) (0.05 g, 0.092 mmol) in dry CH_2Cl_2 was added pyridine (0.03 mL, 0.37 mmol) and trifluoromethanesulfonic anhydride (0.02 mL, 0.12 mmol) at 0 °C. The reaction

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mixture was stirred for 1 h before it was quenched with water. The reaction mixture was diluted with CH_2Cl_2 (10 mL), washed with brine (5.0 mL), dried over Na_2SO_4, and concentrated under a high vacuum. Without further purification, the triflate was dissolved in dry DMF (1.0 mL) and freshly prepared sodium trifluoroethoxide (0.03 g, 0.27 mmol) was added at room temperature. The reaction mixture was stirred for 4 h at room temperature before TLC (10% ethyl acetate in hexane) showed completion. The reaction mixture was quenched with saturated aqueous NH_4Cl solution, extracted with ethyl acetate (2 × 10 mL), dried over Na_2SO_4, and concentrated. Silica gel column chromatography (eluent: 20% EtOAc in hexane) afforded **22** (0.035 g, 61% over two steps) as a semisolid. $[\alpha]_D^{22}$ = −11.0 (*c* 0.55, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.56−7.55 (m, 2H), 7.37−7.21 (m, 18H), 4.79 (d, *J* = 10.2 Hz, 1H), 4.75 (d, *J* = 11.7 Hz, 1H), 4.68−4.67 (m, 1H), 4.66 (d, *J* = 10.3 Hz, 1H), 4.61 (d, *J* = 9.5 Hz, 1H), 4.52 (d, *J* = 11.7 Hz, 1H), 4.49 (d, *J* = 11.7 Hz, 1H), 4.28 (dq, *J* = 12.1, 8.9 Hz, 1H), 3.93 (d, *J* = 2.2 Hz, 1H), 3.92−3.88 (m, 1H), 3.85 (t, *J* = 9.5 Hz, 1H), 3.74 (d, *J* = 9.2, 7.7 Hz, 1H), 3.69 (dd, *J* = 9.2, 5.5 Hz, 1H), 3.61−3.59 (m, 1H), 3.57 (dd, *J* = 9.2, 2.6 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 138.1, 137.8, 137.7, 133.8, 131.5, 129.7, 128.9, 128.8, 128.5, 128.4, 128.4, 128.3, 128.0, 127.9, 127.9, 127.8, 127.7, 127.5, 127.2, 124.7, 122.8, 87.7, 83.7, 77.1, 76.6, 76.0, 75.6, 73.6, 73.4, 69.4 (q, *J* = 34.1 Hz, CF_3CH_2), 68.1. ^{19}F NMR (376 MHz, $CDCl_3$) δ −74.7 (t, *J* = 8.7 Hz, CF_3CH_2O). ^{1}H NMR (600 MHz, C_6D_6) δ 7.66 (d, *J* = 8.2 Hz, 2H), 7.35 (d, *J* = 7.6 Hz, 2H), 7.19 (d, *J* = 7.6 Hz, 2H), 7.16−7.00 (m, 13H), 6.93 (dd, *J* = 10.6, 4.2 Hz, 1H), 4.80 (d, *J* = 10.7 Hz, 1H), 4.54 (d, *J* = 10.7 Hz, 1H), 4.48 (d, *J* = 9.9 Hz, 1H), 4.38 (d, *J* = 11.1 Hz, 1H), 4.23−4.19 (m, 3H), 4.14 (dt, *J* = 17.8, 8.9 Hz, 1H), 3.95 (t, *J* = 9.4 Hz, 1H), 3.68 (dd, *J* = 9.1, 7.6 Hz, 1H), 3.66−3.60 (m, 1H), 3.57 (d, *J* = 1.7 Hz, 1H), 3.55 (dd, *J* = 9.1, 5.7 Hz, 1H), 3.22−3.18 (m, 1H), 3.15 (dd, *J* = 9.2, 2.6 Hz, 1H). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{35}O_5F_3SNa$ [M + Na]$^+$, 647.2055; found, 647.2067.

*Phenyl (6S)-[6-$^2H_1$]-2,3,6-Tri-O-benzyl-4-O-(1′,1′,1′-trifluoroethyl)-1-thio-β-D-galactopyranoside (**6S-D-22**).* Compound **6S-D-22** (0.005 g, 30% over two steps) was synthesized from **6S-D-1** analogously to **22**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.56−7.55 (m, 2H), 7.37−7.21 (m, 18H), 4.78 (d, *J* = 10.1 Hz, 1H), 4.75 (d, *J* = 11.1 Hz, 1H), 4.67 (d, *J* = 11.8 Hz, 1H), 4.65 (d, *J* = 10.2 Hz, 1H), 4.60 (d, *J* = 9.7 Hz, 1H), 4.51 (d, *J* = 11.7 Hz, 1H), 4.49 (d, *J* = 11.6 Hz, 1H), 4.27 (dq, *J* = 12.0, 9.0 Hz, 1H), 3.93 (d, *J* = 2.3 Hz, 1H), 3.92−3.87 (m, 1H), 3.84 (t, *J* = 9.4 Hz, 1H), 3.66 (d, *J* = 5.5 Hz, 1H), 3.60−3.59 (m, 1H), 3.57 (dd, *J* = 9.5, 2.6 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.67 (d, *J* = 7.4 Hz, 2H), 7.35 (d, *J* = 7.4 Hz, 2H), 7.21−7.19 (m, 2H), 7.16−6.90 (m, 14H), 4.80 (d, *J* = 10.7 Hz, 1H), 4.54 (d, *J* = 10.6 Hz, 1H), 4.48 (d, *J* = 9.6 Hz, 1H), 4.37 (d, *J* = 11.8 Hz, 1H), 4.22−4.19 (m, 3H), 4.18−4.10 (m, 1H), 3.95 (t, *J* = 9.4 Hz, 1H), 3.66−3.60 (m, 1H), 3.57 (d, *J* = 2.3 Hz, 1H), 3.53 (d, *J* = 5.6 Hz, 1H, H), 3.19 (d, *J* = 6.0 Hz, 1H), 3.15 (dd, *J* = 9.2, 2.7 Hz, 1H). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{34}DF_3O_5SNa$ [M + Na]$^+$, 648.2118; found, 648.2102.

*Phenyl 4-O-Acetyl-2,3,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**23**).* Compound **23** was synthesized as described in the literature.[86] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.59−7.55 (m, 2H), 7.41−7.21 (m, 18H), 5.01 (dd, *J* = 9.4, 8.7 Hz, 1H), 4.88 (d, *J* = 10.3 Hz, 1H), 4.81 (d, *J* = 11.4 Hz, 1H), 4.70 (d, *J* = 10.3 Hz, 1H), 4.69 (d, *J* = 9.8 Hz, 1H), 4.64 (d, *J* = 11.4 Hz, 1H), 4.51 (s, 2H), 3.67 (dd, *J* = 9.4, 8.8 Hz, 1H), 3.61−3.57 (m, 3H), 3.55 (dd, *J* = 9.8, 8.8 Hz, 1H), 1.85 (s, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.69−7.64 (m, 2H), 7.43−7.39 (m, 2H), 7.33−7.29 (m, 2H), 7.28−7.24 (m, 2H), 7.21−6.94 (m, 12H), 5.33 (dd, *J* = 10.6, 9.2 Hz, 1H), 4.86 (d, *J* = 10.9 Hz, 1H), 4.76 (d, *J* = 11.8 Hz, 1H), 4.64 (d, *J* = 9.6 Hz, 1H), 4.59−4.57 (m, 2H), 4.31 (s, 2H), 3.58 (dd, *J* = 10.6, 3.2 Hz, 1H), 3.54 (dd, *J* = 10.6, 5.8 Hz, 1H), 3.52 (dd, *J* = 9.2, 8.7 Hz, 1H), 3.48 (dd, *J* = 9.6, 8.7 Hz, 1H), 3.36 (ddd, *J* = 10.1, 5.8, 3.2 Hz, 1H), 1.54 (s, 3H). IR (neat) ν 1745 cm^{-1} (C═O).

*Phenyl 2,3,6-Tri-O-benzyl-4-O-trifluoroacetyl-1-thio-β-D-glucopyranoside (**24**).* Compound **2** (0.009 g, 0.016 mmol) was dissolved in anhydrous pyridine (0.05 mL) and cooled to 0 °C before the addition of trifluoroacetic anhydride (4.5 μL, 0.032 mmol). The reaction mixture was then stirred for 4 h under an argon atmosphere and concentrated to dryness. The crude residue was purified by silica gel column chromatography, eluting with hexane/ethyl acetate (7:3), to obtain **24** (0.008 g, 74%) as a colorless oil. $[\alpha]_D^{22}$ = +37.0 (*c* 0.33, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.57−7.54 (m, 2H), 7.41−7.17 (m, 18H), 5.24 (dd, *J* = 9.8, 9.6 Hz, 1H), 4.91 (d, *J* = 10.2 Hz, 1H), 4.81 (d, *J* = 10.8 Hz, 1H), 4.70 (d, *J* = 10.2 Hz, 1H), 4.69 (d, *J* = 9.8 Hz, 1H), 4.62 (d, *J* = 10.8 Hz, 1H), 4.54 (d, *J* = 11.6 Hz, 1H), 4.47 (d, *J* = 11.6 Hz, 1H), 3.77 (dd, *J* = 9.6, 8.8 Hz, 1H), 3.69 (ddd, *J* = 9.8, 4.7, 3.6 Hz, 1H), 3.62 (dd, *J* = 10.7, 3.6 Hz, 1H), 3.58 (dd, *J* = 10.7, 4.7 Hz, 1H), 3.58 (dd, *J* = 9.8, 8.8 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 156.5 (d, *J* = 42.5 Hz), 137.8, 137.6, 137.5, 133.2, 132.4, 129.2, 128.6, 128.5, 128.3, 128.2, 128.1, 128.01, 127.95, 127.9, 114.6 (d, *J* = 285.8 Hz), 87.9, 83.2, 80.8, 76.5, 75.9, 75.7, 74.7, 73.9, 69.1. ^{19}F NMR (376 MHz, $CDCl_3$) δ −75.0 ($OCOCF_3$). ^{1}H NMR (600 MHz, C_6D_6) δ 7.61−7.55 (m, 2H), 7.40−7.36 (m, 2H), 7.27−6.94 (m, 16H), 5.40 (dd, *J* = 10.0, 9.5 Hz, 1H), 4.83 (d, *J* = 10.6 Hz, 1H), 4.71 (d, *J* = 11.3 Hz, 1H), 4.55 (d, *J* = 11.3 Hz, 1H), 4.50 (d, *J* = 10.6 Hz, 1H), 4.46 (d, *J* = 9.7 Hz, 1H), 4.26 (d, *J* = 12.0 Hz, 1H), 4.18 (d, *J* = 12.0 Hz, 1H), 3.43 (dd, *J* = 9.5, 8.7 Hz, 1H), 3.37 (dd, *J* = 10.6, 3.5 Hz, 1H), 3.34 (dd, *J* = 9.7, 8.7 Hz, 1H), 3.30 (dd, *J* = 10.6, 4.3 Hz, 1H), 3.00 (ddd, *J* = 10.0, 4.3, 3.5 Hz, 1H). IR (neat) ν 1793 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{35}H_{33}O_6SF_3Na$ [M + Na]$^+$, 661.1848; found, 661.1843.

*Phenyl 4-O-Benzoyl-2,3,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**25**).* Compound **1** (0.010 g, 0.018 mmol) was dissolved in anhydrous dichloromethane (0.5 mL) and cooled to 0 °C. Anhydrous pyridine (15 μL, 0.18 mmol) was added followed by Tf_2O (10 μL, 0.060 mmol) and the reaction mixture stirred for 1.5 h before it was quenched with water at 0 °C. The reaction mixture was diluted with water and extracted with dichloromethane. The combined organic layers were dried over anhydrous Na_2SO_4 and concentrated to dryness. The crude residue was then dissolved in anhydrous DMF (0.15 mL), and sodium benzoate (7.9 mg, 0.055 mmol) was added. The reaction mixture was stirred under an argon atmosphere at room temperature for 3 h and then diluted with water and extracted with ethyl acetate. The organic layer was separated, dried over anhydrous Na_2SO_4, and concentrated to dryness. The crude residue was purified by column chromatography over silica gel, eluting with hexane/ethyl acetate (8:2) to obtain **25** (0.008 g, 71%) with spectral data consistent with the literature.[76] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.98−7.93 (m, 2H), 7.64−7.53 (m, 3H), 7.44−7.04 (m, 20H), 5.29 (dd, *J* = 10.1, 9.4 Hz, 1H), 4.90 (d, *J* = 10.2 Hz, 1H), 4.77 (d, *J* = 9.8 Hz, 1H), 4.75 (d, *J* = 11.0 Hz, 1H), 4.74 (d, *J* = 10.2 Hz, 1H), 4.62 (d, *J* = 11.0 Hz, 1H), 4.49 (d, *J* = 11.6 Hz, 1H), 4.46 (d, *J* = 11.6 Hz, 1H), 3.83 (dd, *J* = 9.4, 8.7 Hz, 1H), 3.79−3.75 (m, 1H), 3.66−3.64 (m, 2H), 3.62 (dd, *J* = 9.8, 8.7 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.07−8.04 (m, 2H), 7.73−7.68 (m, 2H), 7.45−7.42 (m, 2H), 7.27−6.94 (m, 19H), 5.65 (dd, *J* = 10.0, 9.4 Hz, 1H), 4.89 (d, *J* = 10.8 Hz, 1H), 4.72 (d, *J* = 9.8 Hz, 1H), 4.72 (d, *J* = 11.4 Hz, 1H), 4.62 (d, *J* = 11.4 Hz, 1H), 4.61 (d, *J* = 10.8 Hz, 1H), 4.26−4.20 (m, 2H), 3.68 (dd, *J* = 9.4, 8.6 Hz, 1H), 3.62 (dd, *J* = 10.7, 2.9 Hz, 1H), 3.58 (dd, *J* = 10.7, 6.0 Hz, 1H), 3.54 (dd, *J* = 9.8, 8.6 Hz, 1H), 3.48 (ddd, *J* = 10.0, 6.0, 2.9 Hz, 1H). IR (neat) ν 1726 cm^{-1} (C═O).

*Phenyl 4-O-Benzoyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-25**).* Compound **6S-D-25** (0.030 g, 74%) was synthesized from **6S-D-2** analogously to **25**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.97−7.93 (m, 2H), 7.62−7.54 (m, 3H), 7.45−7.04 (m, 20H), 5.29 (dd, *J* = 10.0, 9.4 Hz, 1H), 4.90 (d, *J* = 10.2 Hz, 1H), 4.77 (d, *J* = 9.8 Hz, 1H), 4.77 (d, *J* = 10.9 Hz, 1H), 4.74 (d, *J* = 10.2 Hz, 1H), 4.62 (d, *J* = 10.9 Hz, 1H), 4.49 (d, *J* = 11.7 Hz, 1H), 4.46 (d, *J* = 11.7 Hz, 1H), 3.83 (dd, *J* = 9.4, 8.8 Hz, 1H), 3.76 (dd, *J* = 10.0, 6.4 Hz, 1H), 3.65−3.60 (m, 2H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.07−8.03 (m, 2H), 7.73−7.68 (m, 2H), 7.46−7.41 (m, 2H), 7.27−6.92 (m, 19H), 5.64 (dd, *J* = 10.0, 9.4 Hz, 1H), 4.89 (d, *J* = 10.7 Hz, 1H), 4.72 (d, *J* = 9.8 Hz, 1H), 4.72 (d, *J* = 11.4 Hz, 1H), 4.62 (d, *J* = 11.4 Hz, 1H), 4.61 (d, *J* = 10.7 Hz, 1H), 4.25 (d, *J* = 11.8 Hz, 1H), 4.22 (d, *J* = 11.8 Hz, 1H), 3.68 (dd, *J* = 9.4, 8.7 Hz, 1H), 3.56 (d, *J* = 6.1 Hz, 1H), 3.54 (dd, *J* = 9.8, 8.7 Hz, 1H), 3.47 (dd, *J* = 10.0, 6.1 Hz,

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1H). HRMS (ESI) m/z calcd for $C_{40}H_{37}DO_6SNa$ $[M + Na]^+$, 670.2350; found, 670.2354.

*Phenyl 4-O-Benzenesulfonyl-2,3,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**26**).* Compound **2** (0.007 g, 0.014 mmol) and 4-dimethylaminopyridine (catalytic amount) were dissolved in anhydrous pyridine (0.1 mL) and cooled to 0 °C. Benzenesulfonyl chloride (5 μL, 0.039 mmol) was added at 0 °C, and the reaction mixture was stirred overnight under an argon atmosphere at room temperature. The reaction mixture was concentrated to dryness, and the crude residue was dissolved in ethyl acetate and filtered through a cotton plug before the organic layer was concentrated to dryness. The crude residue was then purified by silica gel column chromatography, eluting with hexane/ethyl acetate (9:1 to 4:1) to obtain **26** (0.005 g, 57%) as a colorless oil. $[\alpha]_D^{22}$ = +13.3 (*c* 0.15, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.88−7.81 (m, 2H), 7.59−7.16 (m, 23H), 4.82 (dd, *J* = 9.9, 9.2 Hz, 1H), 4.81 (d, *J* = 10.2 Hz, 1H), 4.70 (d, *J* = 11.2 Hz, 1H), 4.63 (d, *J* = 9.8 Hz, 1H), 4.60 (d, *J* = 10.2 Hz, 1H), 4.55 (d, *J* = 11.2 Hz, 1H), 4.49 (d, *J* = 11.6 Hz, 1H), 4.46 (d, *J* = 11.6 Hz, 1H), 3.71 (dd, *J* = 10.8, 2.1 Hz, 1H), 3.66 (dd, *J* = 9.2, 8.7 Hz, 1H), 3.62 (ddd, *J* = 9.9, 5.6, 2.1 Hz, 1H), 3.54 (dd, *J* = 9.8, 8.7 Hz, 1H), 3.51 (dd, *J* = 10.8, 5.6 Hz, 1H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 133.7, 132.2, 129.1, 129.1, 128.5, 128.5, 128.3, 128.1, 127.8, 127.7, 127.6, 127.5, 87.5, 83.7, 81.0, 78.0, 77.8, 75.6, 75.4, 73.5, 68.9. ^{1}H NMR (600 MHz, C_6D_6) δ 7.83−7.77 (m, 2H), 7.67−7.64 (m, 2H), 7.43−6.60 (m, 23H), 5.08 (dd, *J* = 9.9, 9.1 Hz, 1H), 4.80 (d, *J* = 10.4 Hz, 1H), 4.64 (d, *J* = 11.7 Hz, 1H), 4.49 (d, *J* = 9.4 Hz, 1H), 4.47 (d, *J* = 11.7 Hz, 1H), 4.44 (d, *J* = 10.4 Hz, 1H), 4.38 (d, *J* = 11.4 Hz, 1H), 4.36 (d, *J* = 11.4 Hz, 1H), 3.81 (dd, *J* = 10.8, 2.0 Hz, 1H), 3.69 (dd, *J* = 10.8, 5.3 Hz, 1H), 3.45−3.35 (m, 2H), 3.24 (ddd, *J* = 9.9, 5.3, 2.0 Hz, 1H). IR (neat) ν 1360 cm^{-1} (S═O), 1188 cm^{-1} (S═O). HRMS (ESI) m/z calcd for $C_{39}H_{38}O_7S_2Na$ $[M + Na]^+$, 705.1957; found, 705.1954.

*Phenyl 4-O-Benzenesulfonyl-(6S)-[6-$^2H_1$]-2,3,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-26**).* Compound **6S-D-26** (0.005 mg, 62%) was synthesized from **6S-D-2** analogously to **26**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.87−7.81 (m, 2H), 7.60−7.17 (m, 23H), 4.81 (dd, *J* = 9.9, 9.2 Hz, 1H), 4.81 (d, *J* = 10.1 Hz, 1H), 4.70 (d, *J* = 10.8 Hz, 1H), 4.64 (d, *J* = 9.7 Hz, 1H), 4.60 (d, *J* = 10.1 Hz, 1H), 4.55 (d, *J* = 10.8 Hz, 1H), 4.49 (d, *J* = 11.8 Hz, 1H), 4.45 (d, *J* = 11.8 Hz, 1H), 3.66 (dd, *J* = 9.2, 8.7 Hz, 1H), 3.61 (dd, *J* = 9.9, 5.7 Hz, 1H), 3.54 (dd, *J* = 9.7, 8.7 Hz, 1H), 3.50 (d, *J* = 5.7 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.82−7.79 (m, 2H), 7.67−7.64 (m, 2H), 7.43−6.62 (m, 21H), 5.07 (dd, *J* = 9.9, 9.0 Hz, 1H), 4.80 (d, *J* = 10.6 Hz, 1H), 4.64 (d, *J* = 11.6 Hz, 1H), 4.49 (d, *J* = 9.5 Hz, 1H), 4.47 (d, *J* = 11.6 Hz, 1H), 4.45 (d, *J* = 10.6 Hz, 1H), 4.39 (d, *J* = 11.5 Hz, 1H), 4.36 (d, *J* = 11.5 Hz, 1H), 3.67 (d, *J* = 5.3 Hz, 1H), 3.44−3.36 (m, 2H), 3.24 (dd, *J* = 9.9, 5.3 Hz, 1H). HRMS (ESI) m/z calcd for $C_{39}H_{37}DO_7S_2Na$ $[M + Na]^+$, 706.2019; found, 706.2014.

*Phenyl 2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**27**).* Compound **27** was synthesized as described in the literature.[87] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.61−7.58 (m, 2H), 7.41−7.18 (m, 23H), 4.90 (d, *J* = 10.9 Hz, 1H), 4.89 (d, *J* = 10.1 Hz, 1H), 4.85 (d, *J* = 10.9 Hz, 1H), 4.83 (d, *J* = 10.9 Hz, 1H), 4.73 (d, *J* = 10.1 Hz, 1H), 4.67 (d, *J* = 9.8 Hz, 1H), 4.61 (d, *J* = 12.0 Hz, 1H), 4.60 (d, *J* = 10.9 Hz, 1H), 4.55 (d, *J* = 12.0 Hz, 1H), 3.80 (dd, *J* = 10.8, 1.9 Hz, 1H), 3.73 (dd, *J* = 10.8, 4.8 Hz, 1H), 3.71 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.66 (dd, *J* = 9.6, 8.9 Hz, 1H), 3.52 (dd, *J* = 9.8, 8.8 Hz, 1H), 3.51 (ddd, *J* = 9.6, 4.8, 1.9 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.73−7.70 (m, 2H), 7.46−7.42 (m, 2H), 7.35−7.27 (m, 4H), 7.23−6.95 (m, 17H), 4.95 (d, *J* = 10.7 Hz, 1H), 4.89 (d, *J* = 11.3 Hz, 1H), 4.83−4.79 (m, 2H), 4.72 (d, *J* = 10.7 Hz, 1H), 4.65 (d, *J* = 9.6 Hz, 1H), 4.56 (d, *J* = 11.3 Hz, 1H), 4.44 (d, *J* = 12.0 Hz, 1H), 4.35 (d, *J* = 12.0 Hz, 1H), 3.70 (dd, *J* = 9.8, 9.0 Hz, 1H), 3.64−3.62 (m, 2H), 3.61 (dd, *J* = 9.0, 8.7 Hz, 1H), 3.56 (dd, *J* = 9.6, 8.7 Hz, 1H), 3.27−3.23 (m, 1H).

*Phenyl (6S)-[6-$^2H_1$]-2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-27**).* A solution of compound **6S-D-2** (0005 g, 0.008 mmol) in anhydrous DMF (0.2 mL) was cooled to 0 °C and treated with NaH (60%, 1 mg, 0.025 mmol) and benzyl bromide (5.1 μL, 0.025 mmol), respectively. The reaction mixture was then stirred for 3.5 h under an argon atmosphere at room temperature and quenched with water at 0 °C. The aqueous layer was extracted with ethyl acetate, and the organic layer was washed with brine, treated with anhydrous Na_2SO_4, and concentrated to dryness. The crude residue was purified by silica gel column chromatography, eluting with hexane/ethyl acetate (19:1 to 4:1) to obtain **6S-D-27** (0.004 g, 80%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.60−7.56 (m, 2H), 7.41−7.17 (m, 23H), 4.90 (d, *J* = 10.9 Hz, 1H), 4.89 (d, *J* = 10.3 Hz, 1H), 4.85 (d, *J* = 11.0 Hz, 1H), 4.83 (d, *J* = 10.8 Hz, 1H), 4.73 (d, *J* = 10.3 Hz, 1H), 4.67 (d, *J* = 9.8 Hz, 1H), 4.61 (d, *J* = 12.0 Hz, 1H), 4.59 (d, *J* = 10.8 Hz, 1H), 4.55 (d, *J* = 12.0 Hz, 1H), 3.73−3.69 (m, 2H), 3.67−3.61 (m, 1H), 3.51 (dd, *J* = 9.8, 8.7 Hz, 1H), 3.50 (dd, *J* = 9.7, 4.9 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.75−7.67 (m, 2H), 7.46−7.41 (m, 2H), 7.35−6.93 (m, 21H), 4.96 (d, *J* = 10.5 Hz, 1H), 4.89 (d, *J* = 11.4 Hz, 1H), 4.83−4.78 (m, 2H), 4.72 (d, *J* = 10.7 Hz, 1H), 4.65 (d, *J* = 9.6 Hz, 1H), 4.56 (d, *J* = 11.4 Hz, 1H), 4.43 (d, *J* = 12.0 Hz, 1H), 4.36 (d, *J* = 12.0 Hz, 1H), 3.70 (dd, *J* = 9.7, 9.2 Hz, 1H), 3.63−3.59 (m, 2H), 3.56 (dd, *J* = 9.6, 8.8 Hz, 1H), 3.25 (dd, *J* = 9.7, 4.5 Hz, 1H). HRMS (ESI) m/z calcd for $C_{40}H_{39}DO_5SNa$ $[M + Na]^+$, 656.2557; found, 656.2559.

*Ethyl 6-O-Acetyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**28**).* Compound **28** was synthesized as described in the literature.[33] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39−7.24 (m, 15H), 4.95 (d, *J* = 10.9 Hz, 1H), 4.93 (d, *J* = 10.2 Hz, 1H), 4.86 (d, *J* = 10.8 Hz, 1H), 4.85 (d, *J* = 10.9 Hz, 1H), 4.74 (d, *J* = 10.2 Hz, 1H), 4.57 (d, *J* = 10.8 Hz, 1H), 4.47 (d, *J* = 9.8 Hz, 1H), 4.33 (dd, *J* = 11.9, 1.9 Hz, 1H), 4.20 (dd, *J* = 11.9, 5.1 Hz, 1H), 3.71 (dd, *J* = 8.8, 8.7 Hz, 1H), 3.54 (dd, *J* = 9.8, 8.7 Hz, 1H), 3.51 (ddd, *J* = 9.8, 5.1, 1.9 Hz, 1H), 3.44 (dd, *J* = 9.8, 8.8 Hz, 1H), 2.81−2.70 (m, 2H), 2.04 (s, 3H), 1.33 (t, *J* = 7.4 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.43−7.40 (m, 2H), 7.34−7.32 (m, 2H), 7.27−7.25 (m, 2H), 7.20−7.05 (m, 9H), 4.99 (d, *J* = 10.6 Hz, 1H), 4.95 (d, *J* = 11.2 Hz, 1H), 4.81 (d, *J* = 11.2 Hz, 1H), 4.81 (d, *J* = 11.2 Hz, 1H), 4.70 (d, *J* = 10.6 Hz, 1H), 4.49 (d, *J* = 11.2 Hz, 1H), 4.43 (dd, *J* = 11.9, 2.2 Hz, 1H), 4.35 (d, *J* = 9.7 Hz, 1H), 4.26 (dd, *J* = 11.9, 5.4 Hz, 1H), 3.61 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.48 (dd, *J* = 9.8, 8.8 Hz, 1H), 3.47 (dd, *J* = 9.7, 8.9 Hz, 1H), 3.26 (ddd, *J* = 9.8, 5.4, 2.2 Hz, 1H), 2.59 (dq, *J* = 12.6, 7.4 Hz, 1H), 2.49 (dq, *J* = 12.6, 7.4 Hz, 1H), 1.64 (s, 3H), 1.13 (t, *J* = 7.4 Hz, 3H). IR (neat) ν 1742 cm^{-1} (C═O).

*Ethyl 2,3,4-Tri-O-benzyl-6-O-pivolyl-1-thio-β-D-glucopyranoside (**29**).* Compound **3**[33] (0.008 g, 0.016 mmol) was dissolved in anhydrous pyridine (0.05 mL) and treated with pivolyl chloride (2.5 μL, 0.020 mmol). The reaction mixture was then stirred under an argon atmosphere at room temperature overnight and concentrated to dryness. The crude residue was purified by silica gel column chromatography, eluting with hexane/ethyl acetate (4:1 to 7:3) to obtain **29** (0.007 g, 92%) as a colorless oil. $[\alpha]_D^{22}$ = +14.0 (*c* 0.57, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39−7.25 (m, 15H), 4.94 (d, *J* = 10.8 Hz, 1H), 4.93 (d, *J* = 10.2 Hz, 1H), 4.88 (d, *J* = 10.7 Hz, 1H), 4.85 (d, *J* = 10.8 Hz, 1H), 4.74 (d, *J* = 10.2 Hz, 1H), 4.58 (d, *J* = 10.7 Hz, 1H), 4.48 (d, *J* = 9.8 Hz, 1H), 4.44 (dd, *J* = 11.9, 1.8 Hz, 1H), 4.12 (dd, *J* = 11.9, 5.6 Hz, 1H), 3.71 (dd, *J* = 8.8, 8.7 Hz, 1H), 3.53 (ddd, *J* = 9.9, 5.6, 1.8 Hz, 1H), 3.50 (dd, *J* = 9.9, 8.7 Hz, 1H), 3.44 (dd, *J* = 9.8, 8.8 Hz, 1H), 2.78 (dq, *J* = 12.7, 7.4 Hz, 1H), 2.70 (dq, *J* = 12.7, 7.4 Hz, 1H), 1.32 (t, *J* = 7.4 Hz, 3H), 1.21 (s, 9H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 178.2, 138.4, 138.0, 137.8, 128.7, 128.6, 128.6, 128.4, 128.2, 128.0, 128.0, 127.9, 86.7, 84.8, 81.9, 78.2, 76.0, 75.7, 75.4, 63.5, 27.4, 24.9, 15.4. ^{1}H NMR (600 MHz, C_6D_6) δ 7.45−7.41 (m, 2H), 7.35−7.31 (m, 2H), 7.27 (dd, *J* = 8.5, 1.7 Hz, 2H), 7.19−7.05 (m, 9H), 4.99 (d, *J* = 10.6 Hz, 1H), 4.95 (d, *J* = 11.2 Hz, 1H), 4.85 (d, *J* = 11.1 Hz, 1H), 4.82 (d, *J* = 11.2 Hz, 1H), 4.71 (d, *J* = 10.6 Hz, 1H), 4.55 (dd, *J* = 11.9, 2.1 Hz, 1H), 4.50 (d, *J* = 11.1 Hz, 1H), 4.34 (d, *J* = 9.7 Hz, 1H), 4.23 (dd, *J* = 11.9, 5.7 Hz, 1H), 3.60 (dd, *J* = 9.0, 8.8 Hz, 1H), 3.48 (dd, *J* = 9.7, 8.8 Hz, 1H), 3.46 (dd, *J* = 9.8, 9.0 Hz, 1H), 3.26 (ddd, *J* = 9.8, 5.7, 2.1 Hz, 1H), 2.63 (dq, *J* = 12.7, 7.4 Hz, 1H), 2.49 (dq, *J* = 12.7, 7.4 Hz, 1H), 1.18 (s, 9H), 1.16 (t, *J* = 7.4 Hz, 3H). IR (neat) ν 1731 cm^{-1} (C═O). HRMS (ESI) m/z calcd for $C_{34}H_{42}O_6SNa$ $[M + Na]^+$, 601.2600; found, 601.2602.

*Ethyl 2,3,4-Tri-O-benzyl-6-O-trifluoroacetyl-1-thio-β-D-glucopyranoside (**30**).* Compound **30** was synthesized using the same procedure as described for the synthesis of compound **24** from

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compound **3** (0.007 g, 0.014 mmol) and trifluoroacetic anhydride (3.8 μL, 0.028 mmol) in anhydrous pyridine (0.05 mL). After purification by silica gel column chromatography, eluting with hexane/ethyl acetate (7:3), **30** (6.0 mg, 72%) was obtained as a colorless oil. $[\alpha]_D^{22}$ = +16.6 (*c* 0.31, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39−7.23 (m, 15H), 4.96 (d, *J* = 10.9 Hz, 1H), 4.93 (d, *J* = 10.2 Hz, 1H), 4.90 (d, *J* = 11.1 Hz, 1H), 4.85 (d, *J* = 10.9 Hz, 1H), 4.74 (d, *J* = 10.2 Hz, 1H), 4.56 (d, *J* = 11.1 Hz, 1H), 4.54 (dd, *J* = 11.6, 2.1 Hz, 1H), 4.48 (d, *J* = 9.8 Hz, 1H), 4.32 (dd, *J* = 11.6, 6.3 Hz, 1H), 3.72 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.58 (ddd, *J* = 9.9, 6.3, 2.1 Hz, 1H), 3.49 (dd, *J* = 9.9, 8.9 Hz, 1H), 3.45 (dd, *J* = 9.8, 8.8 Hz, 1H), 2.75 (dq, *J* = 12.8, 7.4 Hz, 1H), 2.68 (dq, *J* = 12.8, 7.4 Hz, 1H), 1.30 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 157.27 (q, *J* = 42.5 Hz), 138.3, 137.9, 137.5, 128.8, 128.7, 128.6, 128.4, 128.3, 128.2, 128.1, 127.98, 127.95, 114.6 (q, *J* = 285.4 Hz), 86.7, 85.2, 81.8, 76.3, 76.0, 75.7, 75.3, 66.7, 25.1, 15.2. ^{19}F NMR (376 MHz, $CDCl_3$) δ −74.9($COCF_3$). ^{1}H NMR (600 MHz, C_6D_6) δ 7.42−7.39 (m, 2H), 7.32−7.28 (m, 2H), 7.20−7.06 (m, 11H), 4.95 (d, *J* = 10.6 Hz, 1H), 4.92 (d, *J* = 11.2 Hz, 1H), 4.75 (d, *J* = 11.4 Hz, 1H), 4.75 (d, *J* = 11.2 Hz, 1H), 4.65 (d, *J* = 10.6 Hz, 1H), 4.34 (d, *J* = 11.4 Hz, 1H), 4.24 (dd, *J* = 11.3, 2.4 Hz, 1H), 4.23 (d, *J* = 9.7 Hz, 1H), 4.05 (dd, *J* = 11.5, 6.3 Hz, 1H), 3.51 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.37 (dd, *J* = 9.7, 8.8 Hz, 1H), 3.26 (dd, *J* = 9.9, 8.9 Hz, 1H), 3.07 (ddd, *J* = 9.9, 6.3, 2.2 Hz, 1H), 2.55 (dq, *J* = 12.8, 7.4 Hz, 1H), 2.43 (dq, *J* = 12.8, 7.4 Hz, 1H), 1.12 (t, *J* = 7.4 Hz, 3H). IR (neat) ν 1790 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{31}H_{33}O_6SF_3Na$ $[M + Na]^+$, 613.1848; found, 613.1850.

*Ethyl 6-O-Benzoyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**31**).* Compound **31** was synthesized as described in the literature.[88] ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.07−8.04 (m, 2H), 7.60−7.56 (m, 1H), 7.49−7.40 (m, 4H), 7.39−7.24 (m, 13H), 4.99 (d, *J* = 10.8 Hz, 1H), 4.97 (d, *J* = 10.2 Hz, 1H), 4.91 (d, *J* = 10.8 Hz, 1H), 4.90 (d, *J* = 10.8 Hz, 1H), 4.79 (d, *J* = 10.2 Hz, 1H), 4.66−4.63 (m, 1H), 4.64 (d, *J* = 10.8 Hz, 1H), 4.55 (d, *J* = 9.8 Hz, 1H), 4.48−4.44 (m, 1H), 3.78 (t, *J* = 8.8 Hz, 1H), 3.69−3.67 (m, 2H), 3.52 (dd, *J* = 9.8, 8.8 Hz, 1H), 2.79 (dq, *J* = 12.7, 7.5 Hz, 1H), 2.73 (dq, *J* = 12.7, 7.5 Hz, 1H), 1.32 (d, *J* = 7.5 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.18−8.16 (m, 2H), 7.43−7.40 (m, 2H), 7.34−7.31 (m, 2H), 7.28−7.25 (m, 2H), 7.20−7.01 (m, 12H), 4.98 (d, *J* = 10.6 Hz, 1H), 4.96 (d, *J* = 11.2 Hz, 1H), 4.83 (d, *J* = 11.2 Hz, 1H), 4.81 (d, *J* = 11.1 Hz, 1H), 4.71 (d, *J* = 10.6 Hz, 1H), 4.65 (dd, *J* = 11.8, 2.3 Hz, 1H), 4.52 (d, *J* = 11.1 Hz, 1H), 4.51 (dd, *J* = 11.8, 5.6 Hz, 1H), 4.38 (d, *J* = 9.7 Hz, 1H), 3.64 (dd, *J* = 9.0, 8.8 Hz, 1H), 3.56 (dd, *J* = 9.8, 9.0 Hz, 1H), 3.51 (dd, *J* = 9.6, 8.8 Hz, 1H), 3.36 (ddd, *J* = 9.8, 5.6, 2.3 Hz, 1H), 2.59 (dq, *J* = 12.7, 7.4 Hz, 1H), 2.46 (dq, *J* = 12.7, 7.5 Hz, 1H), 1.11 (d, *J* = 7.5 Hz, 3H). IR (neat) ν 1721 cm^{-1} (C═O).

*Ethyl (6S)-[6-$^2H_1$]-6-O-Benzoyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-31**).* Compound **6S-D-31** (0.007 g, 60%) was synthesized from **6S-D-3** analogously to **31**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.04−8.01 (m, 2H), 7.58−7.54 (m, 1H), 7.46−7.24 (m, 17H), 4.97 (d, *J* = 10.8 Hz, 1H), 4.94 (d, *J* = 10.2 Hz, 1H), 4.89 (d, *J* = 10.7 Hz, 1H), 4.87 (d, *J* = 10.8 Hz, 2H), 4.76 (d, *J* = 10.2 Hz, 1H), 4.62 (d, *J* = 10.7 Hz, 1H), 4.53 (d, *J* = 9.8 Hz, 1H), 4.42−4.40 (m, 1H), 3.76 (dd, *J* = 8.8, 8.7 Hz, 1H), 3.66−3.64 (m, 2H), 3.49 (dd, *J* = 9.7, 8.8 Hz, 1H), 2.77 (dq, *J* = 12.7, 7.5 Hz, 1H), 2.70 (dq, *J* = 12.7, 7.5 Hz, 1H), 1.29 (t, *J* = 7.5 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.19−8.16 (m, 2H), 7.44−7.41 (m, 2H), 7.35−7.32 (m, 2H), 7.28−7.25 (m, 2H), 7.20−7.01 (m, 12H), 4.99 (d, *J* = 10.6 Hz, 1H), 4.96 (d, *J* = 11.3 Hz, 1H), 4.83 (d, *J* = 11.3 Hz, 1H), 4.81 (d, *J* = 11.1 Hz, 1H), 4.71 (d, *J* = 10.6 Hz, 1H), 4.52 (d, *J* = 11.1 Hz, 1H), 4.49 (d, *J* = 5.6 Hz, 1H), 4.37 (d, *J* = 9.7 Hz, 1H), 3.64 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.55 (dd, *J* = 9.8, 8.9 Hz, 1H), 3.51 (dd, *J* = 9.6, 8.8 Hz, 1H), 3.35 (dd, *J* = 9.8, 5.6 Hz, 1H), 2.59 (dq, *J* = 12.8, 7.5 Hz, 1H), 2.46 (dq, *J* = 12.8, 7.5 Hz, 1H), 1.11 (t, *J* = 7.5 Hz, 3H). HRMS (ESI) *m*/*z* calcd for $C_{36}H_{37}DO_6SNa$ $[M + Na]^+$, 622.2350; found, 622.2358.

Ethyl 2,3,4-Tri-O-benzyl-6-O-p-methylbenzoyl-1-thio-β-D-glucopyranoside (32). Compound **3** (0.015 g, 0.030 mmol) was dissolved in anhydrous pyridine (0.1 mL) and cooled to 0 °C before the addition of *p*-methylbenzoyl chloride (5.6 μL, 0.061 mmol). The reaction mixture was then warmed up to room temperature and stirred overnight under an argon atmosphere. The reaction mixture was then diluted with ethyl acetate and washed with aqueous hydrochloric acid (1 M), saturated aqueous $NaHCO_3$, and brine. The organic layer was separated and dried over anhydrous Na_2SO_4 and concentrated to dryness. The resultant crude residue was purified using silica gel column chromatography, eluting with hexane/ethyl acetate (6:1 to 4:1), to afford compound **32** (0.018 g, 95%) as a white semisolid. $[\alpha]_D^{22}$ = +20.5 (*c* 0.6, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.92−7.90 (m, 2H), 7.39−7.37 (m, 2H), 7.35−7.21 (m, 17H), 4.95 (d, *J* = 10.8 Hz, 1H), 4.93 (d, *J* = 10.2 Hz, 1H), 4.87 (d, *J* = 10.7 Hz, 1H), 4.86 (d, *J* = 10.8 Hz, 1H), 4.75 (d, *J* = 10.2 Hz, 1H), 4.60 (d, *J* = 10.7 Hz, 1H), 4.59 (dd, *J* = 12.0, 1.6 Hz, 1H), 4.51 (d, *J* = 9.8 Hz, 1H), 4.40 (dd, *J* = 12.0, 5.2 Hz, 1H), 3.74 (t, *J* = 8.8 Hz, 1H), 3.67−3.63 (m, 2H), 3.48 (dd, *J* = 9.8, 8.8 Hz, 1H), 2.76 (dq, *J* = 12.8, 7.4 Hz, 1H), 2.69 (dq, *J* = 12.8, 7.4 Hz, 1H), 2.40 (s, 3H), 1.28 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 166.4, 143.9, 138.4, 138.0, 137.7, 129.8, 129.2, 128.7, 128.6, 128.4, 128.2, 128.2, 128.1, 128.0, 128.0, 127.4, 86.8, 85.2, 82.0, 78.1, 77.3, 76.1, 75.7, 75.4, 63.8, 25.2, 21.8, 15.3. ^{1}H NMR (600 MHz, C_6D_6) δ 8.17−8.14 (m, 2H), 7.44−7.41 (m, 2H), 7.35−7.32 (m, 2H), 7.29−7.27 (m, 2H), 7.19−7.03 (m, 9H), 6.89−6.86 (m, 2H), 4.99 (d, *J* = 10.6 Hz, 1H), 4.96 (d, *J* = 11.2 Hz, 1H), 4.83 (d, *J* = 11.2 Hz, 1H), 4.82 (d, *J* = 11.0 Hz, 1H), 4.71 (d, *J* = 10.6 Hz, 1H), 4.68 (dd, *J* = 11.8, 2.2 Hz, 1H), 4.54 (dd, *J* = 11.8, 5.7 Hz, 1H), 4.53 (d, *J* = 11.0 Hz, 1H), 4.38 (d, *J* = 9.7 Hz, 1H), 3.64 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.56 (dd, *J* = 9.8, 8.9 Hz, 1H), 3.51 (dd, *J* = 9.7, 8.8 Hz, 1H), 3.37 (ddd, *J* = 9.8, 5.7, 2.2 Hz, 1H), 2.61 (dq, *J* = 12.7, 7.4 Hz, 1H), 2.48 (dq, *J* = 12.7, 7.4 Hz, 1H), 1.95 (s, 3H), 1.13 (t, *J* = 7.4 Hz, 1H). IR (neat) ν 1718 cm^{-1} (C═O). HRMS (ESI) *m*/*z* calcd for $C_{37}H_{40}O_6SNa$ $[M + Na]^+$, 635.2443; found, 635.2474.

*Ethyl (6S)-[6-$^2H_1$]-6-O-p-Methylbenzoyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-32**).* Compound **6S-D-32** (0.003 g, 76%) was synthesized from **6S-D-3** analogously to **32**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.00−7.85 (m, 2H), 7.42−7.20 (m, 19H), 4.99−4.92 (m, 2H), 4.90−4.84 (m, 2H), 4.76 (d, *J* = 10.1 Hz, 1H), 4.61 (d, *J* = 10.7 Hz, 1H), 4.52 (d, *J* = 9.7 Hz, 1H), 4.39 (d, *J* = 5.0 Hz, 1H), 3.75 (t, *J* = 8.8 Hz, 1H), 3.68−3.61 (m, 2H), 3.49 (dd, *J* = 9.7, 8.8 Hz, 1H), 2.82−2.65 (m, 2H), 2.41 (s, 3H), 1.29 (t, *J* = 7.4 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.18−8.14 (m, 2H), 7.44−7.41 (m, 2H), 7.35−7.26 (m, 4H), 7.20−7.02 (m, 9H), 6.89−6.86 (m, 2H), 4.99 (d, *J* = 10.5 Hz, 1H), 4.96 (d, *J* = 11.0 Hz, 1H), 4.83 (d, *J* = 11.0 Hz, 1H), 4.82 (d, *J* = 11.1 Hz, 1H), 4.71 (d, *J* = 10.5 Hz, 1H), 4.53 (d, *J* = 11.1 Hz, 1H), 4.51 (d, *J* = 5.8 Hz, 1H, H), 4.38 (d, *J* = 9.7 Hz, 1H), 3.64 (t, *J* = 8.8 Hz, 1H), 3.56 (dd, *J* = 9.8, 8.8 Hz, 1H), 3.51 (dd, *J* = 9.7, 8.8 Hz, 1H), 3.37 (dd, *J* = 9.8, 5.8 Hz, 1H), 2.65−2.57 (m, 1H), 2.51−2.45 (m, 1H), 1.95 (s, 3H), 1.13 (t, *J* = 7.4 Hz, 3H). HRMS (ESI) *m*/*z* calcd for $C_{37}H_{39}DO_6SNa$ $[M + Na]^+$, 636.2506; found, 636.2508.

*Ethyl 2,3,4-Tri-O-benzyl-6-O-p-methoxybenzoyl-1-thio-β-D-glucopyranoside (**33**).* Compound **33** was synthesized by the same procedure as that described for compound **32** from compound **3** (0.015 g, 0.030 mmol) and *p*-methoxybenzoyl chloride (0.010 g, 0.061 mmol) in anhydrous pyridine (0.1 mL). After purification by silica gel column chromatography, eluting with hexane/ethyl acetate (6:1 to 4:1), compound **33** (0.015 g, 77%) was obtained as a white semisolid. $[\alpha]_D^{22}$ = +23.4 (*c* 0.7, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.00−7.97 (m, 2H), 7.41−7.37 (m, 2H), 7.36−7.23 (m, 13H), 6.93−6.90 (m, 2H), 4.96 (d, *J* = 10.8 Hz, 1H), 4.94 (d, *J* = 10.2 Hz, 1H), 4.88 (d, *J* = 10.8 Hz, 1H), 4.87 (d, *J* = 10.8 Hz, 1H), 4.76 (d, *J* = 10.2 Hz, 1H), 4.61 (d, *J* = 10.8 Hz, 1H), 4.58 (dd, *J* = 11.8, 1.7 Hz, 1H), 4.52 (d, *J* = 9.8 Hz, 1H), 4.41 (dd, *J* = 11.8, 5.2 Hz, 1H), 3.87 (s, 3H), 3.75 (dd, *J* = 8.9, 8.8 Hz, 1H), 3.67−3.63 (m, 2H), 3.49 (dd, *J* = 9.8, 8.8 Hz, 1H), 2.80−2.67 (m, 2H), 1.30 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 166.1, 163.6, 138.4, 138.0, 137.7, 131.7, 128.6, 128.6, 128.4, 128.3, 128.1, 128.1, 128.0, 128.0, 122.5, 113.7, 86.8, 85.2, 82.0, 78.1, 77.3, 76.1, 75.7, 75.4, 63.7, 55.6, 25.2, 15.3. ^{1}H NMR (600 MHz, C_6D_6) δ 8.21−8.18 (m, 2H), 7.44−7.41 (m, 2H), 7.35−7.32 (m, 2H), 7.31−7.28 (m, 2H), 7.20−7.02 (m, 9H), 6.65−6.60 (m, 2H), 5.00 (d, *J* = 10.6 Hz, 1H), 4.96 (d, *J* = 11.3 Hz, 1H), 4.84 (d, *J* = 11.3 Hz, 1H), 4.83 (d, *J* = 11.0 Hz, 1H),

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4.73 (d, J = 10.6 Hz, 1H), 4.69 (dd, J = 11.8, 2.2 Hz, 1H), 4.56 (dd, J = 11.8, 5.6 Hz, 1H), 4.55 (d, J = 11.0 Hz, 1H), 4.39 (d, J = 9.7 Hz, 1H), 3.65 (dd, J = 8.9, 8.7 Hz, 1H), 3.59 (dd, J = 9.8, 8.9 Hz, 1H), 3.54 (dd, J = 9.7, 8.7 Hz, 1H), 3.38 (ddd, J = 9.8, 5.6, 2.2 Hz, 1H), 3.13 (s, 3H), 2.62 (dq, J = 12.7, 7.4 Hz, 1H), 2.49 (dq, J = 12.7, 7.4 Hz, 1H), 1.13 (t, J = 7.4 Hz, 3H). IR (neat) ν 1714 cm^{-1} (C═O). HRMS (ESI) m/z calcd for $C_{37}H_{40}O_7SNa$ $[M + Na]^+$, 651.2392; found, 651.2399.

*Ethyl (6S)-[6-$^2H_1$]-6-O-p-Methoxybenzoyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-33**).* Compound **6S-D-33** (0.004 g, 60%) was synthesized from **6S-D-3** analogously to **33**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.01−7.96 (m, 2H), 7.44−7.22 (m, 15H), 6.94−6.88 (m, 2H), 4.96 (d, J = 10.8 Hz, 1H), 4.94 (d, J = 10.2 Hz, 1H), 4.88 (d, J = 10.8 Hz, 1H), 4.87 (d, J = 10.8 Hz, 1H), 4.76 (d, J = 10.2 Hz, 1H), 4.61 (d, J = 10.8 Hz, 1H), 4.52 (d, J = 9.8 Hz, 1H), 4.39 (d, J = 5.0 Hz, 1H), 3.87 (s, 3H), 3.75 (t, J = 8.8 Hz, 1H), 3.68−3.61 (m, 2H), 3.49 (dd, J = 9.7, 8.8 Hz, 1H), 2.77 (dq, J = 12.7, 7.4 Hz, 1H), 2.70 (dq, J = 12.7, 7.4 Hz, 1H), 1.30 (t, J = 7.4 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 8.22−8.17 (m, 2H), 7.45−7.40 (m, 2H), 7.35−7.32 (m, 2H), 7.30−7.28 (m, 2H), 7.20−7.02 (m, 9H), 6.64−6.60 (m, 2H), 5.00 (d, J = 10.8 Hz, 1H), 4.96 (d, J = 11.2 Hz, 1H), 4.84 (d, J = 11.2 Hz, 1H), 4.83 (d, J = 11.0 Hz, 1H), 4.72 (d, J = 11.0 Hz, 1H), 4.55 (d, J = 10.8 Hz, 1H), 4.53 (d, J = 5.6 Hz, 1H), 4.39 (d, J = 9.7 Hz, 1H), 3.65 (dd, J = 8.9, 8.7 Hz, 1H), 3.58 (dd, J = 9.7, 8.9 Hz, 1H), 3.53 (dd, J = 9.7, 8.7 Hz, 1H), 3.38 (dd, J = 9.7, 5.7 Hz, 1H), 3.13 (s, 3H,), 2.62 (dq, J = 12.7, 7.4 Hz, 1H), 2.49 (dq, J = 12.7, 7.4 Hz, 1H), 1.13 (t, J = 7.4 Hz, 3H). HRMS (ESI) m/z calcd for $C_{37}H_{39}DO_7SNa$ $[M + Na]^+$, 652.2455; found, 652.2468.

*Ethyl 6-O-p-Nitrobenzoyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**34**).* Compound **34** was synthesized using the same procedure as that described for the synthesis of compound **32** from compound **3** (0.015 g, 0.030 mmol) and *p*-nitrobenzoyl chloride (0.011 g, 0.061 mmol) in anhydrous pyridine (0.1 mL). After chromatographic purification using silica gel (hexane/ethyl acetate 6:1 to 4:1), compound **34** (0.019 g, 96%) was obtained as a white semisolid. $[\alpha]_D^{22}$ = +29.7 (c 1.2, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.29−8.26 (m, 2H), 8.17−8.14 (m, 2H), 7.41−7.20 (m, 15H), 4.98 (d, J = 10.8 Hz, 1H), 4.95 (d, J = 10.2 Hz, 1H), 4.90 (d, J = 11.0 Hz, 1H), 4.88 (d, J = 10.8 Hz, 1H), 4.77 (d, J = 10.2 Hz, 1H), 4.62 (dd, J = 11.8, 2.2 Hz, 1H), 4.62 (d, J = 11.0 Hz, 1H), 4.53 (d, J = 9.8 Hz, 1H), 4.44 (dd, J = 11.8, 5.4 Hz, 1H), 3.77 (t, J = 8.8 Hz, 1H), 3.66 (ddd, J = 9.8, 5.4, 2.2 Hz, 1H), 3.61 (dd, J = 9.8, 8.8 Hz, 1H), 3.49 (dd, J = 9.8, 8.8 Hz, 1H), 2.76 (dq, J = 12.7, 7.4 Hz, 1H), 2.70 (dq, J = 12.7, 7.4 Hz, 1H, 1H), 1.29 (t, J = 7.4 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 164.4, 150.7, 138.3, 137.9, 137.6, 135.4, 130.9,128.7, 128.6, 128.4, 128.2, 128.2, 128.1, 128.0, 123.6, 86.8, 85.4, 81.9, 77.6, 76.9, 76.1, 75.7, 75.2, 64.8, 25.3, 15.3. ^{1}H NMR (600 MHz, C_6D_6) δ 7.76−7.73 (m, 2H), 7.66−7.63 (m, 2H), 7.45−7.41 (m, 2H), 7.36−7.33 (m, 2H), 7.26−7.23 (m, 2H), 7.20−6.97 (m, 9H), 5.02 (d, J = 10.6 Hz, 1H), 5.00 (d, J = 11.1 Hz, 1H), 4.85 (d, J = 11.2 Hz, 1H), 4.83 (d, J = 11.1 Hz, 1H), 4.74 (d, J = 10.6 Hz, 1H), 4.56 (dd, J = 11.8, 2.3 Hz, 1H), 4.51 (d, J = 11.2 Hz, 1H), 4.40 (dd, J = 11.8, 5.6 Hz, 1H), 4.37 (d, J = 9.7 Hz, 1H), 3.66 (t, J = 8.8 Hz, 1H), 3.53 (dd, J = 9.7, 8.8 Hz, 1H), 3.50 (dd, J = 9.8, 8.8 Hz, 1H), 3.31 (ddd, J = 9.8, 5.6, 2.3 Hz, 1H), 2.57 (dq, J = 12.7, 7.4 Hz, 1H), 2.46 (dq, J = 12.7, 7.4 Hz, 1H), 1.09 (t, J = 7.4 Hz, 3H). IR (neat) ν 1726 cm^{-1} (C═O). HRMS (ESI) m/z calcd for $C_{36}H_{37}NO_8SNa$ $[M + Na]^+$, 666.2138; found, 666.2148.

*Ethyl (6S)-[6-$^2H_1$]-6-O-p-Nitrobenzoyl-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-34**).* Compound **6S-D-34** (0.004 g, 100%) was synthesized from **6S-D-3** analogously to **34**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.31−8.25 (m, 2H), 8.18−8.12 (m, 2H), 7.44−7.19 (m, 15H), 4.98 (d, J = 10.8 Hz, 1H), 4.95 (d, J = 10.2 Hz, 1H), 4.90 (d, J = 11.0 Hz, 1H), 4.87 (d, J = 10.8 Hz, 1H), 4.76 (d, J = 10.2 Hz, 1H), 4.61 (d, J = 11.0 Hz, 1H), 4.52 (d, J = 9.8 Hz, 1H), 4.42 (d, J = 5.4 Hz, 1H), 3.76 (t, J = 8.8 Hz, 1H), 3.65 (dd, J = 9.8, 5.4 Hz, 1H), 3.60 (dd, J = 9.8, 8.8 Hz, 1H), 3.48 (dd, J = 9.7, 8.8 Hz, 1H), 2.76 (dq, J = 12.7, 7.4 Hz, 1H), 2.70 (dq, J = 12.7, 7.4 Hz, 1H), 1.29 (t, J = 7.4 Hz, 1H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.76−7.72 (m, 2H), 7.66−7.63 (m, 2H), 7.45−7.41 (m, 2H), 7.36−7.33 (m, 2H), 7.26−7.22 (m, 2H), 7.20−6.97 (m, 9H), 5.02 (d, J = 10.7 Hz, 1H), 5.00 (d, J = 11.2 Hz, 1H), 4.85 (d, J = 11.3 Hz, 1H), 4.83 (d, J = 11.2 Hz, 1H), 4.74 (d, J = 10.7 Hz, 1H), 4.51 (d, J = 11.3 Hz, 1H), 4.38 (d, J = 5.5 Hz, 1H), 4.37 (d, J = 9.6 Hz, 1H), 3.66 (t, J = 8.8 Hz, 1H), 3.53 (dd, J = 9.6, 8.8 Hz, 1H), 3.50 (dd, J = 9.8, 8.8 Hz, 1H), 3.30 (dd, J = 9.8, 5.5 Hz, 1H), 2.57 (dq, J = 12.8, 7.4 Hz, 1H), 2.46 (dq, J = 12.8, 7.4 Hz, 1H), 1.09 (t, J = 7.4 Hz, 3H). HRMS (ESI) m/z calcd for $C_{36}H_{36}DNO_8SNa$ $[M + Na]^+$, 667.2200; found, 667.2196.

*Ethyl 2,3,4-Tri-O-benzyl-6-O-(N-phenylcarbamoyl)-1-thio-β-D-glucopyranoside (**35**).* Compound **3** (0.010 g, 0.020 mmol) was dissolved in anhydrous pyridine (0.4 mL) and cooled to 0 °C before the addition of phenyl isothiocyanate (13.3 μL, 0.120 mmol). The reaction mixture was then stirred for 48 h under an argon atmosphere and concentrated to dryness. The crude reaction mixture was dissolved in ethyl acetate and filtered through cotton before it was concentrated to dryness. The crude residue was purified over silica gel column chromatography, eluting with hexane/ethyl acetate (9:1 to 4:1), to afford the compound **35** (0.011 g, 87%) as a white solid with m.p. 119−121 0 °C. $[\alpha]_D^{22}$ = +3.5 (c 0.2, CH_2Cl_2). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39−7.25 (m, 19H), 7.09−7.06 (m, 1H), 6.57 (br s, 1H), 4.96 (d, J = 10.9 Hz, 1H), 4.93 (d, J = 10.2 Hz, 1H), 4.87 (d, J = 10.9 Hz, 1H), 4.86 (d, J = 10.7 Hz, 1H), 4.75 (d, J = 10.2 Hz, 1H), 4.63 (d, J = 10.7 Hz, 1H), 4.49 (d, J = 9.8 Hz, 1H), 4.41−4.35 (m, 2H), 3.73 (t, J = 8.8 Hz, 1H), 3.58−3.52 (m, 2H), 3.45 (dd, J = 9.8, 8.8 Hz, 1H), 2.81−2.70 (m, 2H), 1.31 (t, J = 7.4 Hz, 3H). ^{13}C NMR (150 MHz, $CDCl_3$) δ 153.1, 138.5, 138.0, 137.8, 137.7, 129.2, 128.7, 128.63, 128.6, 128.5, 128.2, 128.1, 127.9, 123.7, 118.7, 86.8, 85.4, 81.9, 77.2, 75.9, 75.7, 75.2, 63.9, 29.9, 25.3, 15.2. ^{1}H NMR (600 MHz, C_6D_6) δ 7.47−7.40 (m, 2H), 7.39−7.30 (m, 4H), 7.29−7.01 (m, 13H), 6.86−6.79 (m, 1H), 6.06 (br s, 1H), 5.01 (d, J = 10.6 Hz, 1H), 4.98 (d, J = 11.4 Hz, 1H), 4.86 (d, J = 11.4 Hz, 1H), 4.83 (d, J = 11.0 Hz, 1H), 4.73 (d, J = 10.6 Hz, 1H), 4.58 (d, J = 11.0 Hz, 1H), 4.46 (dd, J = 11.7, 4.6 Hz, 1H), 4.43 (dd, J = 11.8, 2.5 Hz, 1H), 4.39 (d, J = 9.7 Hz, 1H), 3.66 (dd, J = 9.0, 8.8 Hz, 1H), 3.57−3.52 (m, 2H), 3.29 (ddd, J = 9.8, 4.6, 2.5 Hz, 1H), 2.62 (dq, J = 12.6, 7.4 Hz, 1H), 2.52 (dq, J = 12.6, 7.4 Hz, 1H), 1.13 (t, J = 7.4 Hz, 3H). IR (neat) ν 3329 cm^{-1} (N—H), 1716 cm^{-1} (C═O). HRMS (ESI) m/z calcd for $C_{36}H_{39}NO_6SNa$ $[M + Na]^+$, 636.2396; found, 636.2374.

*Ethyl 2,3,4-Tri-O-benzyl-(6S)-[6-$^2H_1$]-6-O-(N-phenylcarbamoyl)-1-thio-β-D-glucopyranoside (**6S-D-35**).* Compound **6S-D-35** (0.004 g, 100%) was synthesized from **6S-D-3** analogously to **35**. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.31 (m, 19H), 7.10−7.05 (m, 1H), 6.57 (br s, 1H), 4.96 (d, J = 10.8 Hz, 1H), 4.93 (d, J = 10.0 Hz, 1H), 4.87 (d, J = 10.8 Hz, 1H), 4.86 (d, J = 10.6 Hz, 1H), 4.75 (d, J = 10.0 Hz, 1H), 4.62 (d, J = 10.6 Hz, 1H), 4.49 (d, J = 9.8 Hz, 1H), 4.35 (d, J = 4.5 Hz, 1H), 3.72 (t, J = 8.8 Hz, 1H), 3.59−3.50 (m, 2H), 3.44 (dd, J = 9.8, 9.0 Hz, 1H), 2.87−2.66 (m, 2H), 1.31 (t, J = 7.4 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.45−7.41 (m, 2H), 7.37−7.32 (m, 4H), 7.30−7.02 (m, 13H), 6.84−6.79 (m, 1H), 6.04 (br s, 1H), 5.01 (d, J = 10.5 Hz, 1H), 4.98 (d, J = 11.2 Hz, 1H), 4.86 (d, J = 11.2 Hz, 1H), 4.83 (d, J = 11.0 Hz, 1H), 4.73 (d, J = 10.5 Hz, 1H), 4.58 (d, J = 11.0 Hz, 1H), 4.44 (d, J = 4.9 Hz, 1H), 4.38 (d, J = 9.6 Hz, 1H), 3.66 (t, J = 8.7 Hz, 1H), 3.56−3.52 (m, 2H), 3.29 (dd, J = 9.8, 4.9 Hz, 1H), 2.62 (dq, J = 12.6, 7.4 Hz, 1H), 2.52 (dd, J = 12.6, 7.4 Hz, 1H), 1.13 (t, J = 7.4 Hz, 3H). HRMS (ESI) m/z calcd for $C_{36}H_{38}DNO_6SNa$ $[M + Na]^+$, 637.2459; found, 637.2466.

*Ethyl 2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**36**).* Compound **36** was synthesized as described in the literature.[87] ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.40−7.26 (m, 18H), 7.19−7.16 (m, 2H), 4.93 (d, J = 10.9 Hz, 1H), 4.92 (d, J = 10.1 Hz, 1H), 4.86 (d, J = 10.9 Hz, 1H), 4.82 (d, J = 10.7 Hz, 1H), 4.75 (d, J = 10.1 Hz, 1H), 4.61 (d, J = 12.1 Hz, 1H), 4.57 (d, J = 10.7 Hz, 1H), 4.56 (d, J = 12.1 Hz, 1H), 4.47 (d, J = 9.8 Hz, 1H), 3.76 (dd, J = 10.8, 1.9 Hz, 1H), 3.69 (dd, J = 9.0, 8.9 Hz, 1H), 3.69 (dd, J = 10.8, 5.0 Hz, 1H), 3.62 (dd, J = 9.8, 9.0 Hz, 1H), 3.48 (ddd, J = 9.8, 5.0, 1.9 Hz, 1H), 3.45 (dd, J = 9.8, 8.9 Hz, 1H), 2.81 (dd, J = 12.7, 7.5 Hz, 1H), 2.75 (dd, J = 12.7, 7.5 Hz, 1H), 1.34 (d, J = 7.5 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.40−7.00 (m, 20H), 4.94 (d, J = 10.7 Hz, 1H), 4.89 (d, J = 11.3 Hz, 1H), 4.81 (d, J = 11.2 Hz, 1H), 4.79 (d, J = 11.3 Hz, 1H), 4.67 (d, J = 10.7 Hz, 1H), 4.55 (d, J = 11.2 Hz, 1H), 4.41 (d, J = 12.2

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Hz, 1H), 4.36 (d, J = 9.7 Hz, 1H), 4.34 (d, J = 12.2 Hz, 1H), 3.67 (dd, J = 9.7, 9.1 Hz, 1H), 3.61−3.60 (m, 2H), 3.60 (dd, J = 9.1, 8.7 Hz, 1H), 3.46 (dd, J = 9.7, 8.7 Hz, 1H), 3.28−3.24 (m, 1H), 2.59 (dq, J = 12.6, 7.4 Hz, 1H), 2.48 (dq, J = 12.6, 7.4 Hz, 1H), 1.11 (t, J = 7.4 Hz, 3H).

*Ethyl (6S)-[6-$^2H_1$]-2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**6S-D-36**).* Compound **6S-D-36** was synthesized, by the same procedure as that described for **6S-D-27** from **6S-D-3** (0.010 g, 0.020 mmol), NaH (1.0 mg, 0.025 mmol), and benzyl bromide (2.8 μL, 0.024 mmol) in anhydrous DMF (0.1 mL). After purification by silica gel column chromatography, eluting with hexane/ethyl acetate (7:1 to 7:3) gave the title compound (0.011 g, 94%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.40−7.26 (m, 18H), 7.19−7.15 (m, 2H), 4.93 (d, J = 11.0 Hz, 1H), 4.92 (d, J = 10.2 Hz, 1H), 4.85 (d, J = 10.9 Hz, 1H), 4.82 (d, J = 10.8 Hz, 1H), 4.75 (d, J = 10.2 Hz, 1H), 4.60 (d, J = 12.2 Hz, 1H), 4.57 (d, J = 10.8 Hz, 1H), 4.56 (d, J = 12.2 Hz, 1H), 4.47 (d, J = 9.8 Hz, 1H), 3.69 (dd, J = 9.0, 8.9 Hz, 1H), 3.66 (d, J = 5.0 Hz, 1H), 3.61 (dd, J = 9.8, 9.0 Hz, 1H), 3.47 (dd, J = 9.8, 5.0 Hz, 1H), 3.45 (dd, J = 9.8, 8.9 Hz, 1H), 2.80 (dd, J = 12.7, 7.5 Hz, 1H), 2.75 (dd, J = 12.7, 7.5 Hz, 1H), 1.34 (d, J = 7.5 Hz, 3H). ^{1}H NMR (600 MHz, C_6D_6) δ 7.39−7.00 (m, 20H), 4.94 (d, J = 10.7 Hz, 1H), 4.89 (d, J = 11.3 Hz, 1H), 4.81 (d, J = 11.3 Hz, 1H), 4.79 (d, J = 11.3 Hz, 1H), 4.67 (d, J = 10.7 Hz, 1H), 4.55 (d, J = 11.3 Hz, 1H), 4.41 (d, J = 12.2 Hz, 1H), 4.36 (d, J = 9.7 Hz, 1H), 4.35 (d, J = 12.2 Hz, 1H), 3.67 (dd, J = 9.7, 9.1 Hz, 1H), 3.60 (dd, J = 9.1, 8.7 Hz, 1H), 3.59 (d, J = 4.6 Hz, 1H), 3.46 (dd, J = 9.7, 8.7 Hz, 1H), 3.26 (dd, J = 9.7, 4.6 Hz, 1H), 2.59 (dq, J = 12.6, 7.4 Hz, 1H), 2.48 (dq, J = 12.6, 7.4 Hz, 1H), 1.11 (t, J = 7.4 Hz, 3H). HRMS (ESI) m/z calcd for $C_{36}H_{39}DO_5SNa$ $[M + Na]^+$, 608.2557; found, 608.2551.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.8b01459.

Copies of the ^{1}H and ^{13}C NMR spectra of all new compounds (PDF)

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Notes

The authors declare no competing financial interest.

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