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Synthesis of 2-Thiocarbohydrates and Their Binding to Concanavalin A

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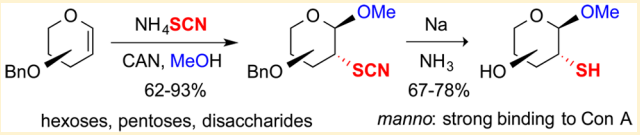
Supporting Information

ABSTRACT: A convenient and general synthesis of 2-thiocarbohydrates via cerium ammonium nitrate oxidation of the thiocyanate ion is described. Radical addition to glycals proceeds with excellent regio- and good stereoselectivities in only one step, deprotection affords water-soluble 2-thio saccharides. Binding studies to Con A have been performed by isothermal titration calorimetry (ITC) and saturation transfer difference (STD) NMR spectroscopy. The 2-thiomannose derivative binds even stronger to Con A than the natural substrate, offering opportunities for new lectin or enzyme inhibitors.



Analogues of naturally occurring carbohydrates are of current interest as enzyme inhibitors and have found various applications in chemistry, biology, and medicine.[1] Especially thiooligosaccharides[2] have been intensively studied, due to their stability against acidic or enzymatic hydrolysis. For instance, thio analogues of kojibioside were obtained already 20 years ago,[3] but new approaches have been published very recently.[4] Furthermore, thiosugars exhibit antiviral activities[5] and even simple 5-thio-D-glucose potentiates the hyperthermic killing of cancer cells.[6]

Although thiosugars are produced in biosynthetic pathways,[7] their chemical synthesis requires many steps. The main strategies for the introduction of sulfur into monosaccharides are opening of epoxides (anhydro sugars)[8] and S_N2 reactions[9] of good leaving groups with thio nucleophiles. Thus, all positions of hexoses have been substituted by these methods.[10] Additionally, 2-thiosugars are available by Michael additions[11] and 1−2 sulfur rearrangements[12] as well. However, the synthesis of the precursors is tedious, requires many steps or expensive starting materials, and overall yields are often moderate. Herein we describe a general and convenient new entry to 2-thiosugars by radical additions to glycals in only few steps and present binding studies to concanavalin A (Con A) as a model system for the first time.

Glycals **1** are suitable precursors for many transformations in carbohydrate chemistry and can be synthesized on a multigram scale with acetyl (Ac) or benzyl (Bn) protecting groups.[13] We have been interested in additions of CH-acidic compounds (e.g., malonates or nitromethane) to their 2-position in the presence of cerium ammonium nitrate (CAN) for many years.[14] More recently, we described the formation of C−P bonds by this oxidant.[15] Thus, based on the pioneering azidonitration of sugars by Lemieux,[16] we became interested in other heteroatom oxidations for applications in carbohydrate chemistry. Thiols cannot be oxidized directly by CAN, due to disulfide formation; however, thiocyanates react conveniently with CAN to generate the corresponding radicals, suitable for additions to simple alkenes and arenes.[17] In carbohydrate chemistry thiocyanates have only been used for nucleophilic substitutions.[8a,18]

We therefore investigated the reaction of various glycals **1** with ammonium thiocyanate (**2**), which is a cheap commercially available reagent, in the presence of CAN (Table 1). No conversion could be achieved with acetyl-protected glucal **1a** (entry 1), presumably due to the higher electrophilicity of thiyl radicals[19] and the low electron density of double bonds of acetyl-protected glycals, which we determined by cyclic voltammetry.[20]

Therefore, *O*-benzyl-protected glycals **1a−f** should be more attractive electron-rich precursors. Indeed, the addition of ammonium thiocyanate (**2**) in the presence of CAN proceeded smoothly at 0 °C and afforded the 2-thiocyanates **3a−f** in moderate to good overall combined yields of 67−93% in only one step (Table 1, entries 2−7). Notably, all isomers could be separated by column chromatography and have been isolated in analytically pure form (Experimental Section); thus, yields of single isomers are sometimes lower.

The presence of the thiocyanato group in the products is evident by characteristic vibration frequencies around 2150 cm^{-1} in the IR[21] and typical chemical shifts of 110 ppm in the ^{13}C NMR spectra. Importantly, the formation of the C−S bond occurs exclusively at the 2-position, proven by high-field shifts of only H-2 in the ^{1}H NMR spectra (Supporting Information). This exclusive regioselectivity is in accordance with orbital control and a radical pathway, discussed in our previous studies.[14] After addition to the double bond, the anomeric radical is oxidized by CAN and finally trapped by methanol to the methyl glycosides **3**.

The stereoselectivities of the reactions are interesting, since two new stereogenic centers are formed in one step. In all examples, the sulfur radicals attack the double bonds of glycals **1** preferentially *anti* to the 3-*O*-benzyl group (Table 1, entries

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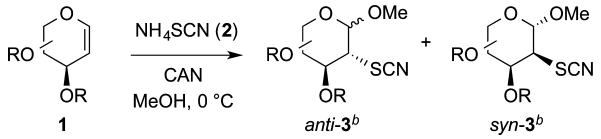
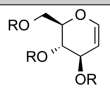
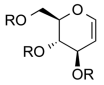
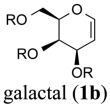
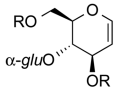
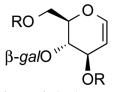
Table 1. Addition of Ammonium Thiocyanate (2) to Glycals 1[a]



entry	glycal	R	β-*anti*-**3** (%)[c]	α-*anti*-**3** (%)[c]	syn-**3** (%)[c]
1	 glucal (**1a**)	Ac	β-*gluco*-**3a** (<3)	α-*gluco*-**3a** (<3)	α-*manno*-**3a** (<3)
2	 glucal (**1a**)	Bn	β-*gluco*-**3a** (44)	α-*gluco*-**3a** (7)	α-*manno*-**3a** (20)[d]
3	 galactal (**1b**)	Bn	β-*galacto*-**3b** (14)	α-*galacto*-**3b** (53)	α-*talo*-**3b** (<3)
4	 xylal (**1c**)	Bn	β-*xylo*-**3c** (63)	α-*xylo*-**3c** (3)	α-*lyxo*-**3c** (16)
5	 arabinal (**1d**)	Bn	β-*arabino*-**3d** (72)[e]	α-*arabino*-**3d** (21)[e]	β-*ribo*-**3d** (<3)[e]
6	 maltal (**1e**)	Bn	β-*malto*-**3e** (45)	α-*malto*-**3e** (<3)	α-*epi-malto*-**3e** (17)
7	 lactal (**1f**)	Bn	β-*lacto*-**3f** (50)	α-*lacto*-**3f** (8)	α-*epi-lacto*-**3f** (16)

[a]Procedure and conditions, see Experimental Section. [b]The nomenclature *anti* and *syn* is related to the relative configurations at C-2 and C-3. [c]Yield of analytically pure products, isolated by column chromatography. [d]Additionally 6% of the β-anomer was isolated. [e]Opposite configurations at C-2 and C-3.

2−7). We established the importance of such steric interactions during the radical addition of malonates to 3-deoxy glucal, which gives almost no selectivity.[20] Furthermore, our results are in accordance to the Wei majority rules for epoxidations of glycals.[22] Although the selectivities of the thiocyanate are somewhat lower than those for malonate additions,[14] they are similar to reactions of phosphonyl radicals with glycals,[15] indicating comparable steric demands. Additionally, in contrast to malonates, the 2-thiocyanate cannot stabilize the finally formed anomeric cation by a neighboring-group participation, resulting in α/β-mixtures of methyl glycosides **3**.

Despite the product mixtures, all reactions afforded one main product, and the isomers could be separated by column chromatography and isolated in analytically pure form, including elemental analysis (Experimental Section). Overall, we developed a general one-step synthesis of carbohydrate 2-thiocyanates from easily available glycals in excellent regio- and good stereoselectivities.

To obtain free thiols for binding studies and to compare our carbohydrate analogues with naturally occurring saccharides, the nitrile group had to be cleaved in the next step. Catalytic hydrogenation of the CN-triple bond, which would cleave the *O*-benzyl groups in the same step is not suitable, due to poisoning of the catalyst by sulfur.[10a,23] Thus, we first investigated reduction of the 2-thiocyanates **3** by lithium aluminum hydride ($LiAlH_4$), which does not affect the protecting groups and allows a convenient isolation of products by column chromatography (Table 2).

Indeed, reaction of thiocyanate β-*gluco*-**3a** with 1 equiv of $LiAlH_4$ afforded thiol β-*gluco*-**4a**, but only in 13%, whereas disulfide **6** was isolated as the main product in 77% yield (entry 1). This might be explained by an oxidation of the intermediary thiolate **7** by air and subsequent dimerization; however, even under careful exclusion of oxygen disulfide **6** was formed. Our mechanistic rationale is based on S_N2 attack of thiolate **7** to unreacted thiocyanate **3**, since cyanide is a good nucleofuge (Scheme 1). To further prove this hypothesis, we generated thiolate β-*gluco*-**7** under argon atmosphere and slowly added thiocyanate β-*gluco*-**3**, and indeed disulfide **6** was formed again (Experimental Section).

To reduce the intermediary formed disulfides **6** during the reaction, an excess of $LiAlH_4$ was employed next, since this reagent is known to reduce S−S bonds.[24] Indeed, under such conditions, the protected thiols **4a−e** were isolated in good yields in analytically pure form (Table 2, entries 2−8, Experimental Section). Finally, to obtain water-soluble compounds for biological studies, the *O*-benzyl groups had to be cleaved. This was conveniently achieved by Birch reduction

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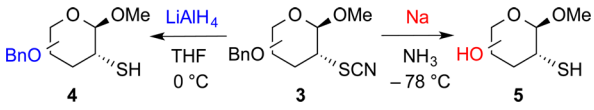
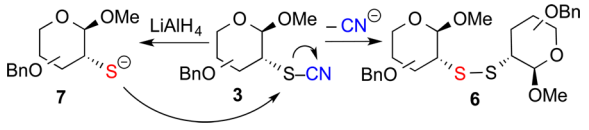
Table 2. Reductions of Carbohydrate 2-Thiocyanates 3[a]



entry	thiocyanate 3	$LiAlH_4$ (equiv)	4 (%)[b]	Na (equiv)	5 (%)[b]
1	*β*-*gluco*-**3a**	1	13[c]	–	–
2	*β*-*gluco*-**3a**	2.5	83	15	78
3	*α*-*manno*-**3a**[d]	2.5	85	15	75
4	*α*-*galacto*-**3b**	2.5	86	15	71
5	*β*-*xylo*-**3c**	2.5	82	12	69
6	*β*-*arabino*-**3d**[d]	2.5	83	12	67
7	*β*-*malto*-**3e**	2.5	84	30	68
8	*β*-*lacto*-**3f**	2.5	93	30	70

[a]Procedure and conditions, see Experimental Section. [b]Yield of analytically pure products, isolated by column chromatography. [c]Additionally 77% of disulfide **6** was isolated. [d]Opposite configurations at C-1 and C-2.

Scheme 1. Proposed Mechanism for the Formation of Disulfide 6



with sodium in liquid ammonia.[10a,25] Under such conditions, the thiocyanates were reduced in the same step, and the free 2-thiosugars **5** were isolated in moderate to good yields by column chromatography (entries 2–9, Na as reducing agent). Again, anaerobic conditions are important to suppress undesired oxidations to disulfides. Overall, starting from glycals **1**, 2-sulfur analogues **5** of naturally occurring methyl glycosides of pentoses, hexoses and disaccharides are available in only 2 steps.

To determine the biological activity of some of our carbohydrate-sulfur analogues, we investigated their binding to concanavalin A (Con A). This plant lectin is commercially available and selectively binds hexoses, depending on their configuration.[26] Thus, galactosides do not interact with Con A, whereas mannopyranosides form stable complexes, which have been characterized by X-ray crystallography.[27] Interestingly, sulfur-linked pseudodisaccharides showed higher affinities to Con A than natural *O*-disaccharides,[10b] maybe due to sulfur acting as hydrogen-bond acceptor. However, to the best of our knowledge, binding constants of free thiols to Con A are hitherto unknown. Since galactosides do not interact with Con A,[28] we focused on *gluco*- and *manno*-configured carbohydrates **5a** and compared their affinities with the literature-known values[26,28] of the corresponding naturally occurring methyl glycosides **8** (Figure 1).

For the measurement of binding constants, isothermal titration calorimetry (ITC) is a well-established method.[29] We started with the *β*-methyl glucoside *gluco*-**8** as reference, since it binds to Con A only very weakly with a dissociation constant K_D = 14 mM.[28a] It turns out that our 2-thio analogue *gluco*-**5a** showed similarly weak binding (K_D > 10 mM), reaching the limit of ITC measurements (Supporting Information, Figure S1).

On the other hand, the naturally occurring *α*-mannoside *manno*-**8** is one of the monosaccharides with the highest affinity towards Con A (K_D = 97 *μ*M).[28b] We could reproduce this

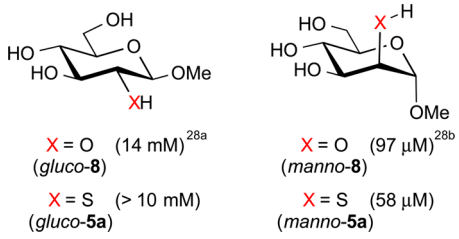


Figure 1. Structures of 2-thio sugars **5a** and methyl glycosides **8** and their binding constants (K_D) to Con A, determined by isothermal titration calorimetry (ITC).

value in our ITC measurements by two independent runs and obtained values of K_D = 98 and 101 *μ*M, respectively (Supporting Information, Figures S2 and S3). Importantly, when we examined our new 2-thio analogue *manno*-**5a** by ITC, we found an even stronger binding of K_D = 57 and 59 *μ*M, respectively, in two repetitive measurements (Figure 1, and Supporting Information, Figures S4 and S5). Such strong binding of monosaccharides to Con A has been hitherto unknown. Thus, the substitution of oxygen by sulfur is important and must be responsible for this effect, providing opportunities for the development of new lectin ligands or enzyme inhibitors. To further characterize the binding of 2-thio sugars **5** to Con A and to gain insight into the binding mode, we applied saturation transfer difference (STD) NMR spectroscopy as the method of choice (Supporting Information).[30] We compared naturally occurring methyl glycosides **8** with our 2-thio analogues *gluco*-**5a** and *manno*-**5a**. Importantly, in contrast to ITC, the weakly binding glucose derivatives can be characterized by STD NMR spectroscopy. Both, the 2-OH as well as the 2-SH derivative show a very similar pattern of STD effects with H-4 being saturated most strongly. That the 2-SH group of *gluco*-**5a** does not increase affinity toward the lectin is also expected, since the equatorial 2-OH/SH groups of the *gluco* derivatives point into solution and are not supposed to make contact with Con A.

As expected, the H-4 of the *manno* derivatives receive strong saturation compatible with the network of H-bonding found in the crystal structure of *α*-methyl mannoside complexed to Con A.[27] However, in contrast to what was observed with the *gluco* derivatives, the 2-SH derivative with *manno* configuration (*manno*-**5a**) shows significantly higher affinity toward Con A, and in the STD NMR experiment we find an altered pattern of STD effects when comparing the 2-OH with the 2-SH derivatives (blue vs red bars, Figures S10 and S11). In case of *manno*-**5a**, H-2 is significantly more strongly saturated than in the 2-OH derivative. This is indicative of an increased contribution of the 2-SH group to binding in conjunction with an altered binding mode that brings H-2 closer to the surface of Con A. In contrast, H-6a/b of *manno*-**5a** are less strongly saturated than in *manno*-**8** (blue vs red bar, Figure S11), indicating again an altered binding mode of *manno*-**5a** with increased distance of its 6-CH_2–group to the binding site of Con A.

Thus, ITC and STD NMR indicate that the thio analogue *manno*-**5a** exhibits a higher affinity to Con A than the naturally occurring monosaccharide *manno*-**8**, furthermore with a different binding mode. Thiol groups are well-known to participate in H-bonding and this has been shown to be important also for carbohydrate recognition.[2d,10a] Thus, an explanation for the increased affinity of *manno*-**5a** might be a

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slightly altered arrangement of H-bonding brought about by the O- to S-substitution. Furthermore, in our ITC experiments with *manno*-**5a** we found only a slightly more favorable enthalpy of binding (approximately $\Delta H = -8.20$ vs -8.35 kcal/mol) but a significantly more favorable entropic contribution ($\Delta S = -9.15$ vs -8.55 cal/molK) (Supporting Information, Figures S2–S5). This would be consistent with increased hydrophobic interactions of *manno*-**5a** and/or solvent rearrangements caused by the replacement of 2-OH with 2-SH. Details of this ligand–lectin interactions will have to be clarified in future work.

In conclusion, we developed an easy new entry to 2-thiocarbohydrates in only two steps from commercially available starting materials. Oxidation of ammonium thiocyanate by CAN and radical addition to various glycals proceeded smoothly with exclusive formation of one regioisomer. The method is applicable to hexoses, pentoses and disaccharides. Stereoselectivities are controlled by steric interactions, and methyl glycosides were isolated in moderate to good yields in analytically pure form. Reduction under different conditions allowed the synthesis of 2-thiols in protected or water-soluble form. An interesting new mechanism for disulfide formation has been proposed. Initial binding studies to Con A have been performed by ITC and STD NMR, and the 2-thiomannose derivative binds even stronger to Con A than the naturally occurring methyl glycoside. Our studies should be interesting for the synthesis of carbohydrate analogues and provide opportunities for the development of new lectin ligands or enzyme inhibitors.

EXPERIMENTAL SECTION

General Information. All compounds were used as purchased without further purification. Unless otherwise stated, all reactions were carried out under nitrogen atmosphere in dry glassware with dried solvents. ^{1}H NMR and ^{13}C NMR spectra were recorded on 300, 500, or 600 MHz spectrometers. 2D experiments (COSY, HSQC, HMBC, coupled HSQC) were performed to assign chemical shifts and to determine the C–H coupling constants. Chemical shifts (δ-scale) are reported in ppm with TMS (0 ppm) as internal standard for ^{1}H NMR and the residual solvent signals ($CDCl_3$: 7.26, D_2O: 4.79 ppm) for ^{1}H NMR and ($CDCl_3$: 77.0 ppm) for ^{13}C NMR. Thin layer chromatography was performed on silica gel coated TLC plates and visualized under UV light (at 254 nm); detection was executed by charring with (sulfuric acid/ethanol/3-methoxy phenol 0.9:99:0.1) solution. High resolution mass spectra were obtained using ESI-Q-TOF or GC/EI-TOF techniques. Elemental analysis was performed on a Vario EL III elemental analyzer.

General Procedure for the Addition of Ammonium Thiocyanate to Glycals..[31,32] Glycal 1 (5 mmol) was dissolved in methanol (50 mL) and cooled to 0 °C. A solution of ammonium thiocyanate 2 (3.81 g, 10 equiv) in methanol (100 mL) and a solution of ceric ammonium nitrate (CAN) (10.96 g, 4 equiv) in methanol (100 mL) was added at this temperature simultaneously using two separate dropping funnels within 2 h until TLC showed complete conversion. After stirring for additional 30 min, an ice-cold solution of sodium sulfite (50 mL) was added and the mixture was extracted with dichloromethane (3 × 80 mL). The combined organic layers were dried over sodium sulfate, concentrated and purified by column chromatography (hexane/ethyl acetate 80:20), affording the 2-thiocyanates 3 in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-gluco-pyranoside (*β-gluco*-3a). Colorless viscous oil (1.11 g, 44%); R_f = 0.51 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +96.3 (c = 1.00 in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ = 2.83 (dd, J = 10.5, 8.5 Hz, 1 H, 2-H), 3.43 (ddd, J = 11.8, 5.7, 2.7 Hz, 1 H, 5-H), 3.53 (s, 3 H, O*Me*), 3.62–3.72 (m, 4 H, 3-H, 4-H, 6-H, 6′-H), 4.36 (d, J = 8.5 Hz, 1 H, 1-H), 4.46 (d, J = 12.2 Hz, 1 H, CH_2-Ph), 4.52 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.56 (d, J = 12.2 Hz, 1 H, CH_2-Ph), 4.72 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.81 (d, J = 10.7 Hz, 1 H, CH_2-Ph), 4.85 (d, J = 10.7 Hz, 1 H, CH_2-Ph), 7.08–7.28 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 53.0 (d, C-2), 57.5 (q, O*Me*), 68.2 (t, C-6), 73.5 (t, CH_2-Ph), 74.9 (d, C-3), 74.9 (t, CH_2-Ph), 76.2 (t, CH_2-Ph), 79.5, 81.5 (2d, C-4, C-5), 101.9 (d, J = 161.5 Hz, C-1), 109.9 (q, SCN), 127.7, 127.8, 127.9, 128.0, 128.4, 128.5 (m, arom. C-H), 137.4, 137.6, 137.9 (3q, arom. C-CH_2O); IR (film) ν = 2865, 2151, 1496, 1453, 1358, 1048, 736, 696 cm^{-1}. Anal. Calcd for $C_{29}H_{31}NO_5S$ (505.62): C, 68.89; H, 6.18; N, 2.77; S, 6.34. Found: C, 68.80; H, 6.23; N, 2.78; S, 6.30.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-gluco-pyranoside (*α-gluco*-3a). Colorless viscous oil (0.17 g, 7%); R_f = 0.44 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +73.5 (c = 1.00 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.30 (dd, J = 10.9, 3.4 Hz, 1 H, 2-H), 3.34 (s, 3 H, O*Me*), 3.59 (dd, J = 11.0, 2.0 Hz, 1 H, 6-H), 3.65 (dd, J = 10.2, 9.0 Hz, 1 H, 4-H), 3.68 (dd, J = 11.0, 3.7 Hz, 1 H, 6′-H), 3.74 (ddd, J = 10.2, 3.7, 2.0 Hz, 1 H, 5-H), 3.89 (dd, J = 10.9, 9.0 Hz, 1 H, 3-H), 4.43 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.44 (d, J = 10.2 Hz, 1 H, CH_2-Ph), 4.54 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.72 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.80 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.84 (d, J = 10.2 Hz, 1 H, CH_2-Ph), 4.85 (d, J = 3.4 Hz, 1 H, 1-H), 7.07–7.32 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 52.8 (d, C-2), 55.6 (q, O*Me*), 67.9 (t, C-6), 71.0 (d, C-5), 73.5, 75.0, 76.2 (3t, CH_2-Ph), 79.2, 80.4 (2d, C-4, C-3), 99.0 (d, J = 170.0 Hz, C-1), 111.6 (q, SCN), 127.6, 127.7, 127.8, 127.8, 127.9, 128.0, 128.4, 128.4 (m, arom. H), 137.4, 137.6, 137.7 (3q, arom. C-CH_2O); IR (film) ν = 2907, 2154, 1496, 1453, 1359, 1044, 735, 696 cm^{-1}. Anal. Calcd for $C_{29}H_{31}NO_5S$ (505.62): C, 68.89; H, 6.18; N, 2.77; S 6.34. Found: C, 68.80; H, 5.82; N, 2.62; S 6.16.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-man-nopyranoside (*α-manno*-3a). Colorless viscous oil (0.49 g, 20%); R_f = 0.44 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +33.9 (c = 1.00 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ = 3.28 (s, 3 H, O*Me*), 3.58 (dd, J = 10.7, 1.9 Hz, 1 H, 6-H), 3.65 (dd, J = 10.7, 4.0 Hz, 1 H, 6′-H), 3.67 (dd, J = 10.7, 8.2 Hz, 1 H, 4-H), 3.70 (ddd, J = 10.7, 4.0, 1.9 Hz, 1 H, 5-H), 3.97 (dd, J = 4.4, 1.6 Hz, 1 H, 2-H), 4.16 (dd, J = 8.2, 4.4 Hz, 1 H, 3-H), 4.37 (d, J = 10.8 Hz, 1 H, CH_2-Ph), 4.42 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.47 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.56 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.68 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.72 (d, J = 10.8 Hz, 1 H, CH_2-Ph), 4.94 (d, J = 1.6 Hz, 1 H, 1-H), 7.04–7.31 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 52.2 (d, C-2), 55.3 (q, O*Me*), 68.4 (t, C-6), 71.4 (d, C-4), 71.8, 73.4 (2t, CH_2-Ph), 73.8 (d, C-5), 75.2 (t, CH_2-Ph), 77.2 (d, C-3), 99.3 (d, J = 172.0 Hz, C-1), 111.8 (q, SCN), 127.6, 127.6, 127.7, 127.9, 128.0, 128.1, 128.3, 128.5 (m, arom. C-H), 137.0, 137.8, 138.0 (3q, arom. C-CH_2O); IR (film) ν = 3030, 2912, 2154, 1496, 1453, 1361, 1056, 736, 696 cm^{-1}. Anal. Calcd for $C_{29}H_{31}NO_5S$ (505.62): C, 68.89; H, 6.18; N, 2.77; S, 6.34. Found: C, 68.83; H, 5.96; N, 2.91; S, 6.72.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-galac-topyranoside (*β-galacto*-3b). White solid (0.35 g, 14%); R_f = 0.53 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +60.1 (c = 1.00 in $CHCl_3$); mp = 72–74 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ = 3.28 (dd, J = 11.0, 8.4 Hz, 1 H, 2-H), 3.49 (s, 3 H, O*Me*), 3.52–3.57 (m, 4 H, 3-H, 5-H, 6-H, 6′-H), 3.96 (d, J = 2.7 Hz, 1 H, 4-H), 4.33 (d, J = 8.4 Hz, 1 H, 1-H), 4.35 (d, J = 11.8 Hz, 1 H, CH_2-Ph), 4.40 (d, J = 11.8 Hz, 1 H, CH_2-Ph), 4.49 (d, J = 11.5 Hz, 1 H, CH_2-Ph), 4.58 (d, J = 11.1 Hz, 1 H, CH_2-Ph), 4.67 (d, J = 11.1 Hz, 1 H, CH_2-Ph), 4.77 (d, J = 11.5 Hz, 1 H, CH_2-Ph), 7.17–7.35 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 50.5 (d, C-2), 57.4 (q, O*Me*), 68.2 (t, C-6), 72.3 (d, C-3), 72.9 (t, CH_2-Ph), 73.4 (d, C-4), 73.6, 74.8 (2t, CH_2-Ph), 79.4 (d, C-5), 102.2 (d, J = 159.4, C-1), 110.2 (q, SCN), 127.7, 127.8, 127.9, 128.1, 128.2, 128.3, 128.5, 128.6, (m, arom. H), 136.9, 137.7, 138.0 (3q, arom. C-CH_2O); IR (film) ν = 2867, 2150, 1496, 1454, 1357, 1063, 739, 699 cm^{-1}. Anal. Calcd for $C_{29}H_{31}NO_5S$ (505.62): C, 68.89; H, 6.18; N, 2.77; S, 6.34. Found: C, 68.67; H, 6.18; N, 2.85; S, 6.35.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-galac-topyranoside (*α-galacto*-3b). Colorless viscous oil (1.35 g, 53%); R_f = 0.53 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +11.4 (c = 1.00 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.28 (s, 3 H, O*Me*), 3.47 (dd, J = 9.4, 6.0 Hz, 1 H, 6-H), 3.49 (dd, J = 9.4, 7.1 Hz, 1 H, 6′-H),

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3.75−3.76 (m, 2 H, 2-H, 3-H), 3.82 (dd, J = 7.1, 4.9 Hz, 1 H, 5-H), 4.06 (dd, J = 4.9, 3.0 Hz, 1 H, 4-H), 4.30 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.39 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.41 (d, J = 11.6 Hz, 1 H, CH_2-Ph), 4.48 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.67 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.82 (d, J = 11.6 Hz, 1 H, CH_2-Ph), 4.99 (s, 1 H, 1-H), 7.15−7.32 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 50.9 (d, C-2), 55.4 (q, O*Me*), 68.6 (t, C-6), 69.7 (d, C-5), 70.5 (t, CH_2-Ph), 73.2 (d, C-4), 73.5 (t, CH_2-Ph), 73.7 (d, C-3), 74.9 (t, CH_2-Ph), 101.2 (d, J = 173.6 Hz, C-1), 115.1 (q, SCN), 127.5, 127.7, 127.7, 128.0, 128.2, 128.3, 128.4, 128.6 (m, arom. H), 137.1, 137.7, 137.8 (3q, arom. *C*-CH_2O); IR (film) ν = 2917, 2150, 1496, 1453, 1348, 1050, 732, 695 cm^{-1}. Anal. Calcd for $C_{29}H_{31}NO_5S$ (505.62): C, 68.89; H, 6.18; N, 2.77; S, 6.34. Found: C, 68.86; H, 6.08; N, 2.83; S, 6.56.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-xylopyranoside (*β-xylo*-3c). Colorless viscous liquid (1.20 g, 63%); R_f = 0.55 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +74.7 (c = 1.00 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ = 2.78 (dd, J = 10.0, 8.2 Hz, 1 H, 2-H), 3.19 (dd, J = 11.8, 10.0 Hz, 1 H, 3-H), 3.47 (s, 3 H, O*Me*), 3.55−3.62 (m, 2 H, 4-H, 5′ H), 3.93 (dd, J = 11.6, 4.7 Hz, 1 H, 5-H), 4.31 (d, J = 8.2 Hz, 1 H, 1-H), 4.55 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.62 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.77 (d, J = 10.7 Hz, 1 H, CH_2-Ph), 4.88 (d, J = 10.7 Hz, 1 H, CH_2-Ph), 7.23−7.29 (m, 10 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 52.5 (d, C-2), 57.3 (q, O*Me*), 63.3 (t, C-5), 73.2, 75.9 (2t, CH_2-Ph), 79.1, 80.0 (2d, C-4, C-3), 102.5 (d, J = 163.4 Hz, C-1), 110.1 (q, SCN), 127.8, 128.0, 128.1, 128.1, 128.4, 128.5 (m, arom. H), 137.5, 137.6 (2q, arom. *C*-CH_2O); IR (film) ν = 2866, 2152, 1497, 1454, 1373, 1077, 738, 696 cm^{-1}. Anal. Calcd for $C_{21}H_{23}NO_4S$ (385.47): C, 65.43; H, 6.01; N, 3.63; S, 8.32. Found: C, 65.46; H, 5.74; N, 3.72; S, 8.34.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-xylopyranoside (*α-xylo*-3c). Colorless viscous liquid (0.065 g, 3%); R_f = 0.48 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = −41.9 (c = 0.50 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.35 (ddd, J = 4.1, 3.1, 1.8 Hz, 1 H, 4-H), 3.36 (s, 3 H, O*Me*), 3.45 (dd, J = 12.4, 3.1 Hz, 1 H, 5-H), 3.72 (t, J = 4.1 Hz, 1 H, 3-H), 3.86 (t, J = 4.1 Hz, 1 H, 2-H), 3.93 (dd, J = 12.4, 1.8 Hz, 1 H, 5′-H), 4.40 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.45 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.51 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.57 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.66 (d, J = 4.1 Hz, 1 H, 1-H), 7.17−7.29 (m, 10 H, arom. H); ^{13}C NMR (150 MHz, $CDCl_3$) δ = 50.2 (d, C-2), 56.5 (q, O*Me*), 57.1 (t, C-5), 71.4 (t, CH_2-Ph), 72.4 (d, C-4), 73.3 (t, CH_2-Ph), 74.1 (d, C-3), 97.8 (d, J = 169.3 Hz, C-1), 112.3 (q, SCN), 127.7, 128.0, 128.1, 128.5, 128.5 (m, arom. H), 136.9, 137.3 (2q, arom. *C*-CH_2O); IR (film) ν = 2927, 2152, 1496, 1454, 1352, 1092, 736, 697 cm^{-1}. Anal. Calcd for $C_{21}H_{23}NO_4S$ (385.47): C, 65.43; H, 6.01; N, 3.63; S, 8.32. Found: C, 65.52; H, 6.23; N, 3.76; S, 8.46.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-lyxopyranoside (*α-lyxo*-3c). Colorless viscous liquid (0.30 g, 16%); R_f = 0.51 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +28.4 (c = 0.54 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.39 (s, 3 H, O*Me*), 3.46 (td, J = 5.3, 3.0 Hz, 1 H, 4-H), 3.71 (dd, J = 12.0, 3.0 Hz, 1 H, 5′-H), 3.73 (dd, J = 6.0, 3.7 Hz, 1 H, 2-H), 3.76 (dd, J = 12.0, 5.3 Hz, 1 H, 5-H), 3.95 (dd, J = 5.3, 3.7 Hz, 1 H, 3-H), 4.47 (d, J = 11.6 Hz, 1 H, CH_2-Ph), 4.49 (d, J = 11.6 Hz, 1 H, CH_2-Ph), 4.55 (dd, J = 11.7 Hz, 2 H, CH_2-Ph), 4.64 (d, J = 6.0 Hz, 1 H, 1-H), 7.16−7.29 (m, 10 H, arom. H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 51.3 (d, C-2), 56.3 (q, O*Me*), 62.1 (t, C-5), 72.0 (t, CH_2-Ph), 72.5 (d, C-4), 72.9 (t, CH_2-Ph), 76.8 (d, C-3), 100.3 (d, J = 168.1 Hz, C-1), 111.8 (q, SCN), 127.7, 127.9, 128.0, 128.2, 128.5, 128.5 (m, arom. H), 136.8, 137.5 (2q, arom. *C*-CH_2O); IR (film) ν = 2162, 1967, 1452, 1357, 1081, 733, 693 cm^{-1}. Anal. Calcd for $C_{21}H_{23}NO_4S$ (385.47): C, 65.43; H, 6.01; N, 3.63; S, 8.32. Found: C, 65.09; H, 6.06; N, 3.73; S, 8.87.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-arabinopyranoside (*β-arabino*-3d). Colorless viscous oil (1.38 g, 72%); R_f = 0.43 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = −65.3 (c = 1.00 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.33 (s, 3 H, O*Me*), 3.56 (t, J = 3.8 Hz, 1 H, 2-H), 3.59 (td, J = 5.0, 2.6 Hz, 1 H, 4-H), 3.67 (dd, J = 12.0, 2.6 Hz, 1 H, 5-H), 3.72 (dd, J = 12.0, 5.0 Hz, 1 H, 5′-H), 4.08 (dd, J = 3.8, 2.6 Hz, 1 H, 3-H), 4.59 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.60 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.61 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.63 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.82 (d, J = 3.8 Hz, 1 H, 1-H), 7.20−7.29 (m, 10 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 51.9 (d, C-2), 56.1 (q, O*Me*), 61.6 (t, C-5), 72.1, 72.3 (2t, CH_2-Ph), 73.2, 74.1 (2d, C-3, C-4), 101.3 (d, J = 171.1 Hz, C-1), 113.9 (q, SCN), 127.7, 127.7, 127.8, 128.0, 128.4, 128.4 (m, arom. H), 137.3, 137.5 (2q, arom. *C*-CH_2O); IR (film) ν = 2874, 2151, 1497, 1453, 1346, 1054, 735, 695 cm^{-1}. Anal. Calcd for $C_{21}H_{23}NO_4S$ (385.47): C, 65.43; H, 6.01; N, 3.63; S, 8.32. Found: C, 65.21; H, 6.09; N, 3.61; S, 8.33.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-arabinopyranoside (*α-arabino*-3d). Colorless viscous oil (0.40 g, 21%); R_f = 0.30 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = −122.2 (c = 1.00 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.27 (dd, J = 13.0, 0.7 Hz, 1 H, 5′-H), 3.30 (dd, J = 10.9, 8.6 Hz, 1 H, 2-H), 3.50 (s, 3 H, O*Me*), 3.51 (dd, J = 10.9, 2.9 Hz, 1 H, 3-H), 3.69 (t, J = 2.9 Hz, 1 H, 4-H), 4.07 (dd, J = 13.0, 2.9 Hz, 1 H, 5-H), 4.25, (d, J = 8.6 Hz, 1 H, 1-H), 4.48 (d, J = 11.4 Hz, 1 H, CH_2-Ph), 4.52 (d, J = 11.4 Hz, 1 H, CH_2-Ph), 4.54 (d, J = 12.2 Hz, 1 H, CH_2-Ph), 4.67 (d, J = 12.2 Hz, 1 H, CH_2-Ph), 7.20−7.28 (m, 10 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 50.3 (d, C-2), 57.3 (q, O*Me*), 63.3 (t, C-5), 71.1 (d, C-4), 71.4, 72.2 (2t, CH_2-Ph), 77.7 (d, C-3), 102.5 (d, J = 160.3 Hz, C-1), 110.2 (q, SCN), 127.8, 127.9, 128.1, 128.1, 128.4, 128.5 (m, arom. H), 136.9, 137.6 (2q, arom. *C*-CH_2O); IR (film) ν = 2867, 2151, 1496, 1454, 1352, 1056, 742, 699 cm^{-1}. Anal. Calcd for $C_{21}H_{23}NO_4S$ (385.47): C, 65.43; H, 6.01; N, 3.63; S, 8.32. Found: C, 65.44; H, 6.35; N, 3.69; S, 8.25.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-maltopyranoside (*β-malto*-3e). Colorless viscous liquid (2.12 g, 45%); R_f = 0.50 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +58.1 (c = 1.00 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 2.92 (dd, J = 10.9, 8.3 Hz, 1 H, 2-H), 3.40 (dd, J = 10.8, 2.2 Hz, 1 H, 6-H), 3.44 (dd, J = 9.8, 3.4 Hz, 1 H, 8-H), 3.47 (ddd, J = 9.4, 3.8, 2.2 Hz, 1 H, 5-H), 3.50 (dd, J = 10.8, 3.8 Hz, 1 H, 6′-H), 3.51 (s, 3 H, O*Me*), 3.55 (dd, J = 10.0, 8.8 Hz, 1 H, 10-H), 3.67 (dd, J = 11.3, 2.3 Hz, 1 H, 12-H), 3.75 (ddd, J = 10.0, 3.8, 2.3 Hz, 1 H, 11-H), 3.79 (dd, J = 10.9, 8.2 Hz, 1 H, 3-H), 3.86 (dd, J = 9.8, 8.8 Hz, 1 H, 9-H), 3.88 (dd, J = 11.3, 3.8 Hz, 1 H, 12′-H), 4.04 (dd, J = 9.4, 8.2 Hz, 1 H, 4-H), 4.28 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.37 (d, J = 8.3 Hz, 1 H, 1-H), 4.39 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.43 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.44 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.46 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.47 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.56 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.69 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.72 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.74 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.80 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 5.01 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 5.30 (d, J = 3.4 Hz, 1 H, 7-H), 7.06−7.20 (m, 30 H, arom. H); ^{13}C NMR (150 MHz, $CDCl_3$) δ = 52.7 (d, C-2), 57.3 (q, O*Me*), 68.3, 68.4 (2t, C-6, C-12), 71.2 (d, C-11), 73.2, 73.3, 73.5, 74.1 (4t, CH_2-Ph), 74.8 (d, C-5), 75.0, 75.6 (2t, CH_2-Ph), 75.6, 77.6, 79.4, 81.5, 81.9 (5d, C-4, C-10, C-8, C-3, C-9), 97.6 (d, C-7), 101.7 (d, J = 162.1 Hz, C-1), 110.0 (q, SCN), 127.4, 127.5, 127.6, 127.6, 127.7, 127.8, 127.9, 128.2, 128.3, 128.3, 128.3, 128.4 (m, arom. *C*-H), 137.5, 137.7, 137.8, 138.0, 138.2, 138.5 (6q, arom. *C*-CH_2O); IR (film) ν = 2866, 2149, 1496, 1453, 1361, 1044, 1026, 732, 694 cm^{-1}. Anal. Calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C, 71.70; H, 6.34; N, 1.49; S, 3.42. Found: C, 71.42; H, 6.18; N, 1.74; S, 3.58.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-*epi*-2-thiocyanato-*α*-D-maltopyranoside (*α-epi-malto*-3e). Colorless viscous liquid (0.806 g, 17%); R_f = 0.38 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +61.4 (c = 1.00 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.27 (dd, J = 10.7, 1.6 Hz, 1 H, 12-H), 3.34 (s, 3 H, O*Me*), 3.40 (dd, J = 9.8, 3.8 Hz, 1 H, 8-H), 3.44 (dd, J = 10.7, 2.6 Hz, 1 H, 12′-H), 3.54 (dd, J = 9.8, 8.4 Hz, 1 H, 9-H), 3.56−5.59 (m, 1 H, 11-H), 3.60 (dd, J = 11.3, 2.2 Hz, 1 H, 6′-H), 3.76 (dd, J = 9.7, 8.4 Hz, 1 H, 10-H), 3.77 (dd, J = 11.3, 4.5 Hz, 1 H, 6-H), 3.85 (ddd, J = 9.1, 4.5, 2.2 Hz, 1 H, 5-H), 3.95 (dd, J = 4.5, 2.2 Hz, 1 H, 2-H), 4.07 (dd, J = 9.1, 8.2 Hz, 1 H, 4-H), 4.17 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.23 (dd, J = 8.2, 4.5 Hz, 1 H, 3-H), 4.31 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.35 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.42−4.45 (m, 4 H, CH_2-Ph), 4.52 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.59 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.68 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.69 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.82 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.94 (d, J = 2.2 Hz, 1 H, 1-H), 5.43 (d, J = 3.8 Hz, 1 H, 7-H), 6.99−7.23 (m, 30 H, arom. H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 51.3 (d, C-2), 55.5 (q, O*Me*), 67.9, 68.8 (2t, C-12, C-6), 69.5, 71.1

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(2d, C-4, C-5), 71.1 (t, CH_2-Ph), 71.2 (d, C-10), 72.9, 73.4, 73.4, 75.0, 75.5 (5t, CH_2-Ph), 77.4, 77.9, 79.3, 81.7 (4d, C-9, C-3, C-8, C-11), 96.9 (d, C-7), 99.2 (d, J = 172.8 Hz, C-1), 111.6 (q, SCN), 127.3, 127.5, 127.6, 127.6, 127.7, 127.7, 127.8, 127.9, 128.0, 128.2, 128.3, 128.3, 128.5 (m, arom. *C*-H), 136.6, 137.8, 137.9, 138.2, 138.3, 138.7 (6q, arom. *C*-CH_2O); IR (Film) ν = 2864, 2153, 1497, 1454, 1361, 1054, 738, 694 cm^{-1}. Anal. Calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C, 71.70; H, 6.34; N, 1.49; S, 3.42. Found: C, 71.44; H, 6.05; N, 1.50; S, 3.40.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-lactopyranoside (*β-lacto*-3f). White solid (2.34 g, 50%); R_f = 0.50 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +40.8 (c = 0.97 in $CHCl_3$); mp = 45−46 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ = 2.78 (dd, J = 10.9, 8.3 Hz, 1 H, 2-H), 3.23−3.26 (m, 1 H, H-11), 3.28 (ddd, J = 9.8, 3.7, 1.9 Hz, 1 H, 5-H), 3.30 (dd, J = 9.8, 3.0 Hz, 1 H, 12-H), 3.32 (dd, J = 7.5, 3.0 Hz, 1 H, 9-H), 3.42 (dd, J = 9.8, 4.9 Hz, 1 H, 12′-H), 3.49 (s, 3 H, O*Me*), 3.52 (dd, J = 10.9, 8.6 Hz, 1 H, 3-H), 3.59 (dd, J = 10.9, 1.9 Hz, 1 H, 6-H), 3.70 (dd, J = 9.8, 7.5 Hz, 1 H, 8-H), 3.76 (dd, J = 10.9, 3.7 Hz, 1 H, 6′-H), 3.83 (d, J = 3.0 Hz, 1 H, 10-H), 3.96 (dd, J = 9.8, 8.6 Hz, 1 H, 4-H), 4.12 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.24 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.29 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.32 (d, J = 11.4 Hz, 1 H, CH_2-Ph), 4.33 (d, J = 8.3 Hz, 1 H, 1-H), 4.46 (d, J = 11.4 Hz, 1 H, CH_2-Ph), 4.47 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.56 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.61 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.65 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.70 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.76 (d, J = 11.4 Hz, 1 H, CH_2-Ph), 4.90 (d, J = 11.4 Hz, 1 H, CH_2-Ph), 5.10 (d, J = 9.8 Hz, 1 H, 7-H), 7.04−7.28 (m, 30 H, arom. H); ^{13}C NMR (150 MHz, $CDCl_3$) δ = 52.8 (d, C-2), 57.4 (q, O*Me*), 67.3, 67.9 (2t, C-6, C-12), 72.5, 73.0 (2t, CH_2-Ph), 73.0 (d, C-10), 73.3 (d, C-11), 73.5, 74.7 (2t, CH_2-Ph), 74.9 (d, C-5), 75.3, 75.9 (2t, CH_2-Ph), 77.2, 79.5, 79.8, 82.3 (4d, C-4, C-3, C-8, C-9), 101.9 (d, C-7), 102.5 (d, J = 162.1 Hz, C-1), 110.2 (q, SCN), 127.3, 127.3, 127.5, 127.5, 127.6, 127.7, 127.7, 127.8, 128.0, 128.1, 128.2, 128.3, 128.4 (m, arom. *C*-H), 137.9, 137.9, 137.9, 138.3, 138.6, 138.8 (6q, arom. *C*-CH_2O); IR (film) ν = 3030, 2871, 2152, 1496, 1453, 1362, 1092, 1061, 733, 695 cm^{-1}. Anal. Calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C, 71.70; H, 6.34; N, 1.49; S, 3.42. Found: C, 72.15; H, 6.00; N, 1.51; S, 3.46.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-lactopyranoside (*α-lacto*-3f). Colorless viscous liquid (0.369 g, 8%); R_f = 0.42 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +41.2 (c = 1.03 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ = 3.20 (dd, J = 11.0, 3.5 Hz, 1 H, 2-H), 3.20−3.25 (m, 2 H, H-6, H-11), 3.27 (dd, J = 9.8, 3.2 Hz, 1 H, 9-H), 3.35 (s, 3 H, O*Me*), 3.38 (dd, J = 12.5, 2.3 Hz, 1 H, 6′-H), 3.45 (dd, J = 11.0, 1.9 Hz, 1 H, 12′-H), 3.59 (dt, J = 10.1, 2.3 Hz, 1 H, 5-H), 3.69 (dd, J = 9.8, 7.6 Hz, 1 H, 8-H), 3.73 (dd, J = 11.0, 8.8 Hz, 1 H, 3-H), 3.79 (dd, J = 11.0, 3.2 Hz, 1 H, 12-H), 3.82 (d, J = 3.2 Hz, 1 H, 10-H), 3.92 (dd, J = 10.1, 8.8 Hz, 1 H, 4-H), 4.11 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.22 (d, J = 7.6 Hz, 1 H, 7-H), 4.24 (d, J = 11.9 Hz, 1 H, CH_2-Ph), 4.28 (d, J = 11.9 Hz, 1 H, CH_2-Ph), 4.46 (d, J = 10.7 Hz, 1 H, CH_2-Ph), 4.48 (d, J = 10.7 Hz, 1 H, CH_2-Ph), 4.56 (d, J = 10.1 Hz, 1 H, CH_2-Ph), 4.61 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.64 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.70 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.76 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.79 (d, J = 3.5 Hz, 1 H, 1-H), 4.89 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 5.06 (d, J = 10.1 Hz, 1 H, CH_2-Ph), 7.05−7.31 (m, 30 H, arom. H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 52.0 (d, C-2), 55.7 (q, O*Me*), 67.4, 68.0 (2t, C-6, C-12), 71.0 (d, C-5), 72.5, 73.2 (2d, CH_2-Ph), 73.2 (d, C-11), 73.3 (d, CH_2-Ph), 73.6 (d, C-10), 74.7, 75.3, 75.7 (3d, CH_2-Ph), 77.3, 77.9, 79.9, 82.3 (4d, C-4, C-3, C-8, C-9), 98.9 (d, J = 169.7 Hz, C-1), 102.7 (d, C-7), 111.4 (q, SCN), 127.3, 127.4, 127.4, 127.5, 127.6, 127.6, 127.7, 127.7, 127.7, 127.8, 127.9, 128.1, 128.3, 128.5 (m, arom. C-H), 137.8, 138.1, 138.1, 138.4, 138.7, 138.9 (6q, arom. *C*-CH_2O); IR (film) ν = 2867, 2156, 1496, 1453, 1362, 1097, 731, 693 cm^{-1}. Anal. Calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C, 71.70; H, 6.34; N, 1.49; S, 3.42. Found: C, 71.61; H, 6.25; N, 1.86; S, 4.42.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-*epi*-2-thiocyanato-*α*-D-lactopyranoside (*α-epi-lacto*-3f). Colorless viscous liquid (0.742 g, 16%); R_f = 0.50 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +7.8 (c = 0.99 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 3.27−3.31 (m, 1 H, H-5), 3.31 (dd, J = 11.9, 1.9 Hz, 1 H, 6-H), 3.32 (s, 3 H, O*Me*), 3.37 (dd, J = 9.4, 5.6 Hz, 1 H, 9-H), 3.41 (dd, J = 9.8, 7.1 Hz, 1 H, 12-H), 3.53 (dd, J = 11.9, 3.8 Hz, 1 H, 6′-H), 3.65 (dd, J = 9.4, 7.5 Hz, 1 H, 8-H), 3.68 (dd, J = 9.8, 4.9 Hz, 1 H, 12′-H), 3.67−3.70 (m, 1 H, 11-H), 3.77 (d, J = 2.9 Hz, 1 H, 10-H), 3.82 (dd, J = 4.5, 3.0 Hz, 1 H, 2-H), 3.89 (dd, J = 8.2, 7.2 Hz, 1 H, 4-H), 4.07 (dd, J = 7.2, 4.5 Hz, 1 H, 3-H), 4.18 (d, J = 11.6 Hz, 1 H, CH_2-Ph), 4.26 (d, J = 7.5 Hz, 1 H, 7-H), 4.30 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.30 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.46 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.49 (d, J = 11.6 Hz, 1 H, CH_2-Ph), 4.55 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.59 (d, J = 11.7 Hz, 1 H, CH_2-Ph), 4.62 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.63 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.65 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.70 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.86 (d, J = 11.3 Hz, 1 H, CH_2-Ph), 4.88 (d, J = 3.0 Hz, 1 H, 1-H), 7.13−7.26 (m, 30 H, arom. H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 52.0 (d, C-2), 55.6 (q, O*Me*), 68.2, 68.7 (2t, C-6, C-12), 71.7 (d, C-10), 72.4, 72.7, 73.2, 73.4 (4t, CH_2-Ph), 73.5, 73.5, 74.3 (3d, C-11, C-5, C-4), 74.6, 75.2 (2t, CH_2-Ph), 76.2, 79.6, 82.4 (3d, C-3, C-8, C-9), 99.5 (d, C-7), 103.5 (d, J = 173.0 Hz, C-1), 111.9 (q, SCN), 127.5, 127.5, 127.5, 127.6, 127.7, 127.8, 127.8, 128.0, 128.2, 128.3, 128.4, (m, arom. *C*-H), 137.8, 137.9, 138.2, 138.3, 138.6, 138.6 (6q, arom. *C*-CH_2O); IR (film) ν = 3063, 2864, 2009, 1496, 1453, 1362, 1062, 1026, 732, 695 cm^{-1}. Anal. Calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C, 71.70; H, 6.34; N, 1.49; S, 3.42. Found: C, 71.50; H, 6.06; N, 1.60; S, 3.72.

General Procedure for the Lithium Aluminum Hydride Reduction of 2-Thiocyanates 3 to Free 2-Thiols 4. ***Caution!*** *The reaction and workup has to be performed in a fume hood under careful handling, due to the liberation of highly toxic HCN.* 2-Thiocyanate **3** (0.5 mmol) was dissolved in dry tetrahydrofuran (15 mL) and cooled to 0 °C under nitrogen atmosphere. Lithium aluminum hydride (48 mg, 1.25 mmol, 2.5 equiv) was added at this temperature and the solution was stirred for 30 min until TLC showed complete conversion. The reaction mixture was slowly quenched with ice and filtered through Celite. Tetrahydrofuran was removed in vacuo and the resulting residue was extracted with dichloromethane (3 × 20 mL) and water (20 mL). The combined organic layers were dried over sodium sulfate, concentrated and purified by column chromatography (hexane/MTBE 85:15), affording the 2-thiols **4** in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*β*-D-glucopyranoside (*β-gluco*-4a). White solid (200 mg, 83%); R_f = 0.53 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +17.7 (c = 1.00 in $CHCl_3$); mp = 45−46 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ = 1.92 (d, J = 3.2 Hz, 1 H, S*H*), 2.97 (ddd, J = 10.6, 8.5, 3.2 Hz, 1 H, 2-H), 3.35 (dd, J = 10.6, 8.7 Hz, 1 H, 3-H), 3.38 (ddd, J = 9.4, 3.8, 1.7 Hz, 1 H, 5-H), 3.42 (s, 3 H, O*Me*), 3.54 (dd, J = 9.4, 8.7 Hz, 1 H, 4-H), 3.68 (dd, J = 10.7, 1.7 Hz, 1 H, 6-H), 3.65 (dd, J = 10.7, 3.8 Hz, 1 H, 6′-H), 4.09 (d, J = 8.5 Hz, 1 H, 1-H), 4.43 (d, J = 12.2 Hz, 1 H, CH_2-Ph), 4.45 (d, J = 10.8 Hz, 1 H, CH_2-Ph), 4.52 (d, J = 12.2 Hz, 1 H, CH_2-Ph), 4.69 (d, J = 10.8 Hz, 1 H, CH_2-Ph), 4.71 (d, J = 10.6 Hz, 1 H, CH_2-Ph), 4.76 (d, J = 10.6 Hz, 1 H, CH_2-Ph), 7.06−7.29 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 46.1 (d, C-2), 57.0 (q, O*Me*), 68.7 (t, C-6), 73.5, 74.8 (2t, CH_2-Ph), 75.2 (d, C-3), 75.4 (t, CH_2-Ph), 79.0, 84.8 (2d, C-4, C-5), 104.7 (d, C-1), 127.6, 127.7, 127.8, 127.8, 128.0, 128.4 (m, arom. C−H), 137.9, 137.9, 138.0 (3q, arom. *C*-CH_2O); IR (film) ν = 2862, 1496, 1453, 1359, 1046, 735, 696 cm^{-1}. Anal. Calcd for $C_{28}H_{32}O_5S$ (480.61): C, 69.97; H, 6.71; S, 6.67. Found: C, 70.16; H, 6.45; S, 6.60.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*α*-D-mannopyranoside (*α-manno*-4a). Colorless viscous liquid (204 mg, 85%); R_f = 0.51 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +38.5 (c = 0.98 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 1.77 (d, J = 7.9 Hz, 1 H, S*H*), 3.24 (s, 3 H, O*Me*), 3.41 (ddd, J = 7.9, 4.5, 1.5 Hz, 1 H, 2-H), 3.61 (dd, J = 12.4, 3.8 Hz, 1 H, 6-H), 3.65−3.68 (m, 1 H, 5-H), 3.68 (dd, J = 12.4, 3.4 Hz, 1 H, 6′-H), 3.87 (dd, J = 9.5, 9.0 Hz, 1 H, 4-H), 4.01 (dd, J = 9.0, 4.5 Hz, 1 H, 3-H), 4.38 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.43 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.49 (d, J = 11.5 Hz, 1 H, CH_2-Ph), 4.57 (d, J = 11.5 Hz, 1 H, CH_2-Ph), 4.58 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.74 (d, J = 1.5 Hz, 1 H, 1-H), 4.77 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 7.07−7.30 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 42.5 (d, C-2), 54.9 (q, O*Me*), 68.9 (t, C-6), 71.3 (t, CH_2-Ph), 71.3 (d, C-5), 73.3 (t, CH_2-Ph), 73.9 (d, C-4), 74.9 (t, CH_2-Ph),

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78.3 (d, C-3), 101.1 (d, C-1), 127.4, 127.5, 127.6, 127.7, 127.8, 127.8, 128.2, 128.3 (m, arom. C−H), 138.0, 138.2, 138.3 (3q, arom. *C*-CH_2O); IR (film) ν = 2906, 2067, 1496, 1452, 1360, 1053, 733, 695 cm^{-1}. Anal. Calcd for $C_{28}H_{32}O_5S$ (480.61): C, 69.97; H, 6.71; S, 6.67. Found: C, 70.14; H, 6.87; S, 6.72.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-α-D-galactopyranoside (*α-galacto*-4b). Colorless viscous liquid (207 mg, 86%); R_f = 0.55 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +2.7 (*c* = 0.97 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ = 2.93 (d, *J* = 11.1 Hz, 1 H, S*H*), 3.28 (ddd, *J* = 11.1, 6.4, 1.2 Hz, 1 H, 2-H), 3.99 (s, 3 H, O*Me*), 3.72−3.73 (m, 2 H, 6-H, 6′-H), 3.92−3.93 (m, 1 H, 5-H), 4.02 (dd, *J* = 3.9, 1.7 Hz, 1 H, 4-H), 4.04 (dd, *J* = 6.4, 1.7 Hz, 1 H, 3-H), 4.50 (d, *J* = 11.8 Hz, 1 H, CH_2-Ph), 4.55 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 4.59 (d, *J* = 11.8 Hz, 1 H, CH_2-Ph), 4.62 (d, *J* = 11.5 Hz, 1 H, *CH*$_2$-Ph), 4.83 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 5.03 (d, *J* = 1.2 Hz, 1 H, 1-H), 5.11 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 7.28−7.49 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 40.2 (d, C-2), 55.1 (q, O*Me*), 69.3 (t, C-6), 69.8 (d, C-4), 70.0, 73.5 (2t, CH_2-Ph), 73.9, 74.3 (2d, C-3, C-5), 75.0 (t, CH_2-Ph), 104.7 (d, C-1), 127.4, 127.6, 127.6, 127.6, 128.0, 128.1, 128.3, 128.3 (m, arom. C−H), 138.1, 138.1, 138.6 (3q, arom. *C*-CH_2O); IR (film) ν = 2909, 1452, 1353, 1109, 1148, 951, 732, 695 cm^{-1}. Anal. Calcd for $C_{28}H_{32}O_5S$ (480.61): C, 69.97; H, 6.71; S, 6.67. Found: C, 69.91; H, 6.80; S, 6.90.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-β-D-xylopyranoside (*β-xylo*-4c). Colorless viscous liquid (147 mg, 82%); R_f = 0.57 (hexane/ethyl acetate 7:3); $[\alpha]_D^{20}$ = +6.7 (*c* = 1.01 in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ = 1.99 (d, *J* = 3.5 Hz, 1 H, S*H*), 2.88 (ddd, *J* = 10.3, 8.2, 3.5 Hz, 1 H, 2-H), 3.17 (dd, *J* = 11.6, 9.9 Hz, 1 H, 5-H), 3.32 (dd, *J* = 10.3, 8.4 Hz, 1 H, 3-H), 3.41 (s, 3 H, O*Me*), 3.53 (ddd, *J* = 9.9, 8.4, 5.1 Hz, 1 H, 4-H), 3.94 (dd, *J* = 11.6, 5.1 Hz, 1 H, 5′-H), 4.08 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.53 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 4.62 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 4.69 (d, *J* = 10.8 Hz, 1 H, *CH*$_2$-Ph), 4.84 (d, *J* = 10.8 Hz, 1 H, *CH*$_2$-Ph), 7.16−7.33 (m, 10 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 45.5 (d, C-2), 56.9 (q, O*Me*), 63.8 (t, C-5), 73.1, 75.3 (2t, CH_2-Ph), 78.8, 83.4 (2d, C-3, C-4), 105.3 (d, C-1), 127.8, 127.9, 128.1, 128.4, 128.5 (m, arom. C−H), 137.9, 138.0 (2q, arom. *C*-CH_2O); IR (film) ν = 2857, 1725, 1496, 1453, 1371, 1057, 736, 696 cm^{-1}. Anal. Calcd for $C_{20}H_{24}O_4S$ (360.46): C, 66.64; H, 6.71; S, 8.90. Found: C, 66.83; H, 6.46; S, 8.78.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-β-D-arabinopyranoside (*β-arabino*-4d). Colorless viscous liquid (150 mg, 83%); R_f = 0.45 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = −30.5 (*c* = 1.00 in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ = 2.11 (d, *J* = 9.3 Hz, 1 H, S*H*), 2.76 (ddd, *J* = 9.3, 7.4, 3.1 Hz, 1 H, 2-H), 3.43 (s, 3 H, O*Me*), 3.57 (ddd, *J* = 8.2, 5.2, 3.1 Hz, 1 H, 4-H), 3.76 (dd, *J* = 11.0, 5.2 Hz, 1 H, 5-H), 3.78 (dd, *J* = 11.0, 8.2 Hz, 1 H, 5′-H), 3.95 (t, *J* = 3.1 Hz, 1 H, 3-H), 4.40 (d, *J* = 7.4 Hz, 1 H, 1-H), 4.53 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.58 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.59 (d, *J* = 11.1 Hz, 1 H, CH_2-Ph), 4.84 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 7.13−7.34 (m, 10 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 44.0 (d, C-2), 56.7 (q, O*Me*), 62.1 (t, C-5), 71.7, 74.4 (2t, CH_2-Ph), 76.4, 77.0 (2d, C-3, C-4), 103.6 (d, C-1), 127.4, 127.6, 127.7, 127.8, 128.2, 128.4 (m, arom. C−H), 137.9, 138.3 (2q, arom. *C*-CH_2O); IR (film) ν = 2871, 2572, 1496, 1453, 1372, 1057, 736, 696 cm^{-1}. Anal. Calcd for $C_{20}H_{24}O_4S$ (360.46): C, 66.64; H, 6.71; S, 8.90. Found: C, 66.62; H, 6.62; S, 9.15.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thio-β-D-maltopyranoside (*β-malto*-4e). Colorless viscous liquid (383 mg, 84%); R_f = 0.52 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +33.6 (*c* = 0.96 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ = 2.02 (d, *J* = 3.5 Hz, 1 H, S*H*), 3.10 (ddd, *J* = 10.4, 8.2, 3.5 Hz, 1 H, 2-H), 3.38 (dd, *J* = 10.6, 2.1 Hz, 1 H, 12-H), 3.42 (dd, *J* = 9.7, 3.5 Hz, 1 H, 8-H), 3.46 (s, 3 H, O*Me*), 3.49 (dd, *J* = 10.6, 3.3 Hz, 1 H, 12′-H), 3.50 (ddd, *J* = 9.2, 4.1, 2.2 Hz, 1 H, 5-H), 3.55 (dd, *J* = 10.1, 9.1 Hz, 1 H, 10-H), 3.62 (dd, *J* = 10.4, 8.5 Hz, 1 H, 3-H), 3.69 (dd, *J* = 11.0, 2.2 Hz, 1 H, 6-H), 3.72 (ddd, *J* = 10.1, 3.3, 2.1 Hz, 1 H, 11-H), 3.80 (dd, *J* = 11.0, 4.1 Hz, 1 H, 6′-H), 3.83 (dd, *J* = 9.7, 9.1 Hz, 1 H, 9-H), 4.03 (dd, *J* = 9.2, 8.5 Hz, 1 H, 4-H), 4.15 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.27 (d, *J* = 12.3 Hz, 1 H, CH_2-Ph), 4.39 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 4.43−4.49 (m, 5 H, CH_2-Ph), 4.60 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 4.70 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 4.73 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 4.80 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 4.82 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 5.40 (d, *J* = 3.5 Hz, 1 H, 7-H), 7.05−7.26 (m, 30 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 44.7 (d, C-2), 56.9 (q, O*Me*), 68.4, 69.1 (2t, C-6, C-12), 70.8 (t, CH_2-Ph), 71.1, 72.7 (2d, C-11, C-4), 73.0, 73.3, 73.4, 75.0 (4t, CH_2-Ph), 75.1 (d, C-5), 75.5 (t, CH_2-Ph), 77.6, 79.4, 81.8, 84.3 (4d, C-10, C-8, C-9, C-3), 96.6, 104.6 (2d, C-7, C-1), 127.4, 127.5, 127.6, 127.6, 127.7, 127.7, 127.8, 127.8, 128.0, 128.2, 128.3 (m, arom. C−H), 137.8, 137.8, 137.9, 138.2, 138.3, 138.7 (6q, arom. *C*-CH_2O); IR (film) ν = 3024, 2867, 1495, 1357, 1086, 1024, 729, 693 cm^{-1}. Anal. Calcd for $C_{55}H_{60}O_{10}S$ (913.12): C, 72.34; H, 6.62; S, 3.51. Found: C, 72.14; H, 6.63; S, 3.57.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thio-β-D-lactopyranoside (*β-lacto*-4f). White solid (425 mg, 93%); R_f = 0.51 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +7.4 (*c* = 1.02 in $CHCl_3$); mp = 107−108 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ = 2.00 (d, *J* = 2.6 Hz, 1 H, S*H*), 2.96 (ddd, *J* = 10.5, 8.3, 2.6 Hz, 1 H, 2-H), 3.25 (dd, *J* = 10.9, 5.0 Hz, 1 H, 6-H), 3.29 (dd, *J* = 10.5, 8.6 Hz, 1 H, 3-H), 3.29−3.32 (m, 1 H, 5-H), 3.31 (dd, *J* = 9.8, 3.0 Hz, 1 H, 9-H), 3.33 (ddd, *J* = 3.7, 1.5, 1.0 Hz, 1 H, 11-H), 3.43 (dd, *J* = 10.9, 4.0 Hz, 1 H, 6′-H), 3.43 (s, 3 H, O*Me*), 3.63 (dd, *J* = 10.9, 1.5 Hz, 1 H, 12-H), 3.70 (dd, *J* = 9.8, 7.5 Hz, 1 H, 8-H), 3.77 (dd, *J* = 10.9, 3.7 Hz, 1 H, 12′-H), 3.83 (dd, *J* = 3.0, 1.0 Hz, 1 H, 10-H), 3.89 (dd, *J* = 10.2, 8.6 Hz, 1 H, 4-H), 4.12 (d, *J* = 8.3 Hz, 1 H, 1-H), 4.13 (d, *J* = 11.6 Hz, 1 H, CH_2-Ph), 4.24 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.30 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.32 (d, *J* = 7.5 Hz, 1 H, 7-H), 4.46 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.48 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.51 (d, *J* = 10.6 Hz, 1 H, CH_2-Ph), 4.61 (d, *J* = 12.1 Hz, 1 H, CH_2-Ph), 4.64 (d, *J* = 12.1 Hz, 1 H, CH_2-Ph), 4.72 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 4.74 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 4.89 (d, *J* = 11.6 Hz, 1 H, CH_2-Ph), 5.04 (d, *J* = 10.6 Hz, 1 H, CH_2-Ph), 7.05−7.30 (m, 30 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 45.8 (d, C-2), 56.9 (q, O*Me*), 68.0, 68.0 (2t, C-6, C-12), 72.6 (t, CH_2-Ph), 73.0 (d, C-9), 73.1, 73.4 (2t, CH_2-Ph), 73.7 (d, C-8), 74.7, 75.0, 75.3 (3t, CH_2-Ph), 75.5, 76.8, 79.9, 82.4, 82.9 (5d, C-11, C-4, C-10, C-5, C-3), 102.7, 104.6 (2d, C-7, C-1), 127.3, 127.4, 127.4, 127.5, 127.6, 127.6, 127.7, 127.8, 127.8, 128.0, 128.1, 128.2, 128.2, 128.3, 128.4 (m, arom. C−H), 138.0, 138.2, 138.5, 138.5, 138.7, 139.0 (6q, arom. *C*-CH_2O); IR (film) ν = 3029, 2862, 1495, 1364, 1098, 1024, 732, 695 cm^{-1}. Anal. Calcd for $C_{55}H_{60}O_{10}S$ (913.13): C, 72.34; H, 6.62; S, 3.51. Found: C, 72.02; H, 6.44; S, 3.69.

Control Experiment for the Formation of Disulfide *β-gluco*-6. ***Caution!*** *The reaction and workup has to be performed in a fume hood under careful handling, due to the liberation of highly toxic HCN.* To a solution of thiol *β-gluco*-**4a** (120 mg, 0.25 mmol) in dry dimethylformamide (2 mL) was added sodium hydride (60% dispersion in mineral oil, 20 mg, 0.5 mmol, 2 equiv) under argon at room temperature and it was allowed to stir for 10 min. A solution of thiocyanate *β-gluco*-**3a** (126 mg, 0.25 mmol, 1 equiv) in dry dimethylformamide (2 mL) was added dropwise to the above solution over a period of 5 min. The resulting reaction mixture was stirred for 1 h until TLC showed complete conversion and quenched with ice−water (25 mL) followed by extraction with diethyl ether (3 × 25 mL). The combined organic layers were washed with brine (25 mL), dried over sodium sulfate, concentrated and purified by column chromatography to afford disulfide *β-gluco*-**6** (183 mg, 76%) in analytically pure form. Note: The disulfide *β*-gluco-**6** (200 mg, 77%) has been also formed during the reduction of thiocyanate *β-gluco*-**3a**, when 1 equiv of lithium aluminum hydride was used.

Bis[methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2,2′-disulfido-β-D-glucopyranoside](*β-gluco*-6). Colorless viscous liquid; R_f = 0.20 (hexane/ethyl acetate 8:2); $[\alpha]_D^{20}$ = +136.9 (*c* = 0.83 in $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$) δ = 2.71 (dd, *J* = 10.8, 8.6 Hz, 1 H, 2-H), 2.99 (ddd, *J* = 10.1, 4.2, 2.3 Hz, 1 H, 5-H), 3.49 (dd, *J* = 10.8, 8.7 Hz, 1 H, 3-H), 3.50 (s, 3 H, O*Me*), 3.52 (dd, *J* = 10.9, 2.3 Hz, 1 H, 6-H), 3.54 (dd, *J* = 10.1, 8.7 Hz, 1 H, 4-H), 3.56 (dd, *J* = 10.9, 4.2 Hz, 1 H, 6′-H), 4.35 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.45 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.49 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 4.54 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.71 (d, *J* = 10.8 Hz, 1 H, CH_2-Ph), 4.80 (bs, 2 H, CH_2-Ph), 7.08−7.31 (m, 15 H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 56.3 (q, O*Me*), 58.0 (d, C-2), 68.6 (t, C-6), 73.4 (t, CH_2-Ph), 74.4 (d, C-5), 74.7, 75.9 (2t, CH_2-Ph), 79.5, 81.3 (2d, C-3, C-4), 102.8 (d, C-1),

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127.5, 127.6, 127.6, 127.7, 127.8, 128.2, 128.3, 128.4 (m, arom. C−H), 138.1, 138.1, 138.1 (3q, arom. C-CH_2O); IR (film) ν = 3029, 2862, 1952, 1604, 1453, 1357, 1106, 1044, 735, 695 cm^{-1}. Anal. Calcd for $C_{56}H_{62}O_{10}S_2$ (859.21): C, 70.12; H, 6.51; S, 6.69. Found: C, 69.79; H, 6.66; S, 6.93.

General Procedure for the Birch Reduction of 2-Thiocyanates 3 to Free 2-Thiols 5. In a three necked round-bottom flask ammonia (50 mL) was condensed at −78 °C using a dry ice-acetone bath. Small pieces of freshly cut sodium (5 equiv per benzyl group) were added which leads to a dark blue colored solution. To this reducing solution, 2-thiocyanate **3** (0.5 mmol) dissolved in dry tetrahydrofuran (3 mL) was added, followed by a few drops of methanol. After vigorous stirring for 10 min, the reaction mixture was quenched with solid ammonium chloride and ammonia was allowed to evaporate (the blue color of the reducing mixture persists until the completion of reaction which turns to white upon quenching). The resulting residue was purified by column chromatography (DCM/MeOH 90:10) followed by lyophilization, affording the free 2-thiols **5** in analytically pure form.

Methyl-2-deoxy-2-thio-β-D-glucopyranoside (*β-gluco*-5a). White solid (82 mg, 78%); R_f = 0.33 (dichloromethane/methanol 8:2); $[\alpha]_D^{20}$ = −8.9 (c = 0.96 in H_2O); mp = 126−127 °C; ^{1}H NMR (500 MHz, D_2O) δ = 2.70 (dd, J = 10.2, 8.8 Hz, 1 H, 2-H), 3.34 (dd, J = 10.2, 8.9 Hz, 1 H, 3-H), 3.40 (dd, J = 9.6, 8.9 Hz, 1 H, 4-H), 3.47 (ddd, J = 9.6, 6.0, 2.2 Hz, 1 H, 5-H), 3.55 (s, 3 H, O*Me*), 3.72 (dd, J = 12.3, 6.0 Hz, 1 H, 6-H), 3.91 (dd, J = 12.3, 2.2 Hz, 1 H, 6′-H), 4.41 (d, J = 8.8 Hz, 1 H, 1-H); ^{13}C NMR (75 MHz, D_2O) δ = 47.1 (d, C-2), 58.1 (q, O*Me*), 61.7 (t, C-6), 71.5, 76.8, 77.4 (3d, C-4, C-5, C-3), 105.2 (d, C-1); IR (film) ν = 3356, 2927, 1591, 1447, 1379, 1064, 819, 603 cm^{-1}. Anal. Calcd for $C_7H_{14}O_5S$ (210.24): C, 39.99; H, 6.71; S, 15.25. Found: C, 40.59; H, 6.84; S, 15.41; HRMS (EI) m/z $[M + H]^+$ Calcd for $C_7H_{14}O_5S$ 211.0665, found 211.0654.

Methyl-2-deoxy-2-thio-α-D-mannopyranoside (*α-manno*-5a). White solid (79 mg, 75%); R_f = 0.34 (dichloro methane/methanol 8:2); $[\alpha]_D^{20}$ = −143.9 (c = 0.99 in H_2O); mp = 108−109 °C; ^{1}H NMR (600 MHz, D_2O) δ = 3.37 (s, 3 H, O*Me*), 3.41 (d, J = 5.4 Hz, 1 H, 2-H), 3.60 (dd, J = 9.5, 5.4 Hz, 1 H, 3-H), 3.63−3.67 (m, 1H, 5-H), 3.74 (dd, J = 12.2, 5.4 Hz, 1 H, 6-H), 3.84 (dd, J = 12.2, 5.4 Hz, 1 H, 6′-H), 4.00 (dd, J = 9.5, 4.6 Hz, 1 H, 4-H), 4.90 (s, 1 H, 1-H); ^{13}C NMR (150 MHz, $CDCl_3$) δ = 44.4 (d, C-2), 54.8 (q, O*Me*), 60.6 (t, C-6), 66.4, 69.0, 72.9 (3d, C-4, C-5, C-3), 102.4 (d, C-1); IR (Film) ν = 3381, 2919, 1653, 1346, 1195, 1024, 952, 600 cm^{-1}. Anal. Calcd for $C_7H_{14}O_5S$ (210.24): C, 39.99; H, 6.71; S, 15.25. Found: C, 37.65; H, 6.25; S, 15.22; HRMS (EI) m/z $[M + H]^+$ Calcd for $C_7H_{14}O_5S$ 211.0665, found 211.0648.

Methyl-2-deoxy-2-thio-α-D-galactopyranoside (*α-galacto*-5b). White solid (75 mg, 71%); R_f = 0.34 (dichloro methane/methanol 8:2); $[\alpha]_D^{20}$ = −142.1 (c = 1.03 in H_2O); mp = 111−112 °C; ^{1}H NMR (500 MHz, D_2O) δ = 3.26 (dd, J = 5.3, 1.0 Hz, 1 H, 2-H), 3.38 (s, 3 H, O*Me*), 3.74 (dd, J = 11.7, 4.1 Hz, 1 H, 6-H), 3.81 (dd, J = 11.7, 7.9 Hz, 1 H, 6′-H), 3.89−3.92 (m, 1 H, 5-H), 3.90 (dd, J = 3.4, 1.4 Hz, 1 H, 4-H), 4.09 (dd, J = 5.3, 3.4 Hz, 1 H, 3-H), 5.02 (d, J = 1.0 Hz, 1 H, 1-H); ^{13}C NMR (125 MHz, D_2O) δ = 42.2 (d, C-2), 55.7 (q, O*Me*), 62.3 (t, C-6), 65.6, 69.5, 72.0 (3d, C-3, C-4, C-5), 104.7 (d, C-1); IR (film) ν = 3332, 2904, 2068, 1660, 1334, 1111, 1038, 952, 759 cm^{-1}; HRMS (ESI-TOF) m/z $[M + Na]^+$ Calcd for $C_7H_{14}O_5SNa$ 233.0460, found 233.0463.

Methyl-2-deoxy-2-thio-β-D-xylopyranoside (*β-xylo*-5c). White solid (62 mg, 69%); R_f = 0.55 (hexane/ethyl acetate 1:9); $[\alpha]_D^{20}$ = −18.2 (c = 1.05 in $CHCl_3$); mp = 100−101 °C; ^{1}H NMR (300 MHz, D_2O) δ = 2.68 (dd, J = 10.4, 8.8 Hz, 1 H, 2-H), 3.33 (dd, J = 10.8, 6.0 Hz, 1 H, 5-H), 3.35 (dd, J = 10.4, 3.4 Hz, 1 H, 3-H), 3.53 (s, 3 H, O*Me*), 3.57 (ddd, J = 6.0, 5.5, 3.4 Hz, 1 H, 4-H), 4.00 (dd, J = 10.8, 5.5 Hz, 1 H, 5′-H), 4.35 (d, J = 8.8 Hz, 1 H, 1-H); ^{13}C NMR (75 MHz, D_2O) δ = 46.5 (d, C-2), 57.7 (q, O*Me*), 65.6 (t, C-5), 70.5, 76.9 (2d, C-4, C-3), 105.6 (d, C-1); IR (film) ν = 3390, 2922, 1667, 1452, 1148, 1057, 805 cm^{-1}; HRMS (ESI-TOF) m/z $[M + Na]^+$ Calcd for $C_6H_{12}O_4SNa$ 203.0354, found 203.0347.

Methyl-2-deoxy-2-thio-β-D-arabinopyranoside (*β-arabino*-5d). Colorless viscous liquid (60 mg, 67%); R_f = 0.55 (hexane/ethyl acetate 1:9); $[\alpha]_D^{20}$ = −68.7 (c = 1.07 in $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ = 2.96 (dd, J = 5.3, 3.9 Hz, 1 H, 2-H), 3.39 (s, 3 H, O*Me*), 3.65 (dd, J = 12.9, 8.5 Hz, 1 H, 5-H), 3.78 (dd, J = 12.9, 3.9 Hz, 1 H, 5′-H), 3.79 (dd, J = 8.5, 3.9 Hz, 1 H, 4-H), 3.99 (t, J = 3.9 Hz, 1 H, 3-H), 4.57 (d, J = 5.3 Hz, 1 H, 1-H); ^{13}C NMR (125 MHz, $CDCl_3$) δ = 44.0 (d, C-2), 56.4 (q, O*Me*), 63.3 (t, C-5), 68.0, 68.4 (2d, C-3, C-4), 102.9 (d, C-1); IR (film) ν = 3387, 2987, 2548, 1651, 1457, 1204, 1086, 791, 476 cm^{-1}; HRMS (ESI-TOF) m/z $[M + Na]^+$ Calcd for $C_6H_{12}O_4SNa$ 203.0354, found 203.0360.

Methyl-2-deoxy-2-thio-β-D-maltopyranoside (*β-malto*-5e). White solid (127 mg, 68%); R_f = 0.22 (dichloromethane/methanol 8:2); $[\alpha]_D^{20}$ = +44.3 (c = 0.98 in H_2O); mp = 174−176 °C; ^{1}H NMR (600 MHz, D_2O) δ = 2.76 (dd, J = 11.0, 8.6 Hz, 1 H, 2-H), 3.42 (dd, J = 11.0, 9.0 Hz, 1 H, 3-H), 3.58 (s, 3 H, O*Me*), 3.58 (dd, J = 9.8, 3.7 Hz, 1 H, 8-H), 3.62 (ddd, J = 8.9, 5.0, 2.1 Hz, 1 H, 11-H), 3.62−3.64 (m, 1 H, 10-H), 3.68 (dd, J = 10.2, 9.0 Hz, 1 H, 4-H), 3.70−3.74 (m, 1 H, 9-H), 3.72 (ddd, J = 10.2, 4.5, 2.1 Hz, 1 H, 5-H), 3.77 (dd, J = 12.6, 5.0 Hz, 1 H, 12-H), 3.79 (dd, J = 12.1, 4.5 Hz, 1 H, 6-H), 3.86 (dd, J = 12.6, 2.1 Hz, 1 H, 12′-H), 3.95 (dd, J = 12.1, 2.1 Hz, 1 H, 6′-H), 4.45 (d, J = 8.6 Hz, 1 H, 1-H), 5.41 (d, J = 3.7 Hz, 1 H, 7-H); ^{13}C APT NMR (150 MHz, D_2O) δ = 45.9 (d, C-2), 56.9 (q, O*Me*), 60.1, 60.3 (2t, C-6, C-12), 68.9, 71.3, 72.3, 72.4, 74.1, 76.4, 77.2 (7d, C-3, C-8, C-4, C-9, C-10, C-5, C-11), 99.3, 103.8 (2d, C-7, C-1); IR (film) ν = 3376, 2924, 1633, 1400, 1194, 1113, 1025, 800, 600 cm^{-1}; HRMS (ESI-TOF) m/z $[M + Na]^+$ Calcd for $C_{13}H_{24}O_{10}SNa$ 395.0988, found 395.1010.

Methyl-2-deoxy-2-thio-β-D-lactopyranoside (*β-lacto*-5f). White solid (130 mg, 70%); R_f = 0.23 (dichloromethane/methanol 8:2); $[\alpha]_D^{20}$ = +4.1 (c = 1.05 in H_2O); mp = 190−191 °C; ^{1}H NMR (600 MHz, D_2O) δ = 2.75 (dd, J = 10.5, 8.7 Hz, 1 H, 2-H), 3.54 (dd, J = 10.1, 7.5 Hz, 1 H, 8-H), 3.57 (s, 3 H, O*Me*), 3.60 (dd, J = 11.2, 1.2 Hz, 1 H, 12-H), 3.61−3.64 (m, 1 H, 11-H), 3.63 (dd, J = 9.1, 7.5 Hz, 1 H, 4-H), 3.67 (dd, J = 10.1, 3.3 Hz, 1 H, 9-H), 3.72−3.74 (m, 1 H, 5-H), 3.74 (dd, J = 10.5, 9.1 Hz, 1 H, 3-H), 3.77 (dd, J = 11.2, 3.0 Hz, 1 H, 12′-H), 3.82 (dd, J = 12.2, 4.4 Hz, 1 H, 6-H), 3.93 (dd, J = 3.3, 1.1 Hz, 1 H, 10-H), 3.99 (dd, J = 12.2, 1.6 Hz, 1 H, 6′-H), 4.46 (d, J = 8.7 Hz, 1 H, 1-H), 4.46 (d, J = 7.5 Hz, 1 H, 7-H); ^{13}C APT NMR (150 MHz, D_2O) δ = 45.5 (d, C-2), 57.3 (q, O*Me*), 60.1, 61.0 (2t, C-6, C-12), 68.5, 70.9, 72.4, 74.6, 74.9, 75.3, 79.2 (7d, C-10, C-8, C-9, C-5, C-4, C-3, C-11), 102.9, 104.1 (2d, C-7, C-1); IR (film) ν = 3326, 2930, 1635, 1403, 1115, 1015, 891, 605 cm^{-1}; HRMS (ESI-TOF) m/z $[M + Na]^+$ Calcd for $C_{13}H_{24}O_{10}SNa$ 395.0988, found 395.0971.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00987.

NMR spectra, ITC and STD NMR measurements (PDF)

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Notes

The authors declare no competing financial interest.

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