Glycosyl cations in glycosylation reactions

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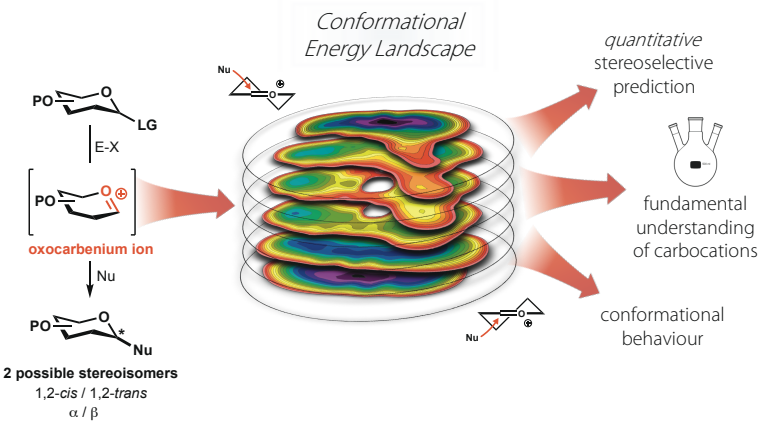
Chapter 2

Defining the S_N1 Side of Glycosylation Reactions: Stereoselectivity of Glycopyranosyl Cations



Abstract | The broad application of well-defined synthetic oligosaccharides in glycobiology and glycobiotechnology is largely hampered by the lack of sufficient amounts of synthetic carbohydrate specimens. Insufficient knowledge of the glycosylation reaction mechanism thwarts the routine assembly of these materials. Glycosyl cations are key reactive intermediates in the glycosylation reaction but their high reactivity and fleeting nature have precluded the determination of clear structure-reactivity-stereoselectivity principles for these species. This chapter describes a combined experimental and computational method that connects the stereoselectivity of oxocarbenium ions to the full ensemble of conformations these species can adopt, quantitatively mapped in conformational energy landscapes (CEL). The detailed description of stereoselective S_N1-type glycosylation reactions firmly establishes glycosyl cations as true reaction intermediates and will enable the generation of new stereoselective glycosylation methodologies.

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Introduction

Carbohydrates play numerous roles in living organisms, as key players in energy housekeeping, structural components, and signaling molecules. To unravel the role carbohydrates play in biological processes, well-defined single molecules are indispensable and organic synthesis has been one of the major suppliers for pure oligosaccharide specimens to fuel glycobiological and glycomedical research. Although significant progress has been made in the field, the generation of sufficient amounts of synthetic (complex) oligosaccharides remains a difficult and time-consuming undertaking.[1–5] The main obstacle in the construction of oligosaccharides is the stereoselective construction of 1,2-*cis*-glycosidic linkages.[6,7] While 1,2-*trans* linkages can be reliably installed using a neighboring group participation approach, there is no general solution for the construction of 1,2-*cis* linkages. Different reaction pathways can be followed during a glycosylation reaction and these can lead to different diastereomeric products. Figure 1 depicts the current understanding of the continuum of mechanisms that is operational during a glycosylation reaction.[8–10]

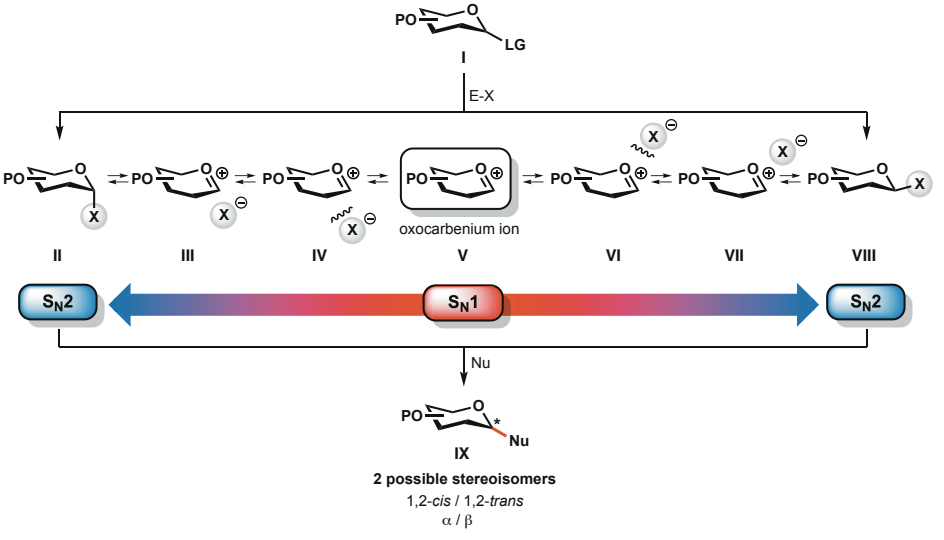


Figure 1. The reaction mechanism continuum operational during glycosylation reactions. Glycosylation reactions are best considered as taking place at a continuum between two formal extremes of an S_N1- and S_N2 mechanism; **I**: donor substrate; **II**: reactive covalent α-intermediate; **III**: contact ion pair, with the leaving group associated at the α-face; **IV**: solvent separated ion pair, with the leaving group that has departed from the α-face; **V**: solvent separated oxocarbenium ion; **VI**: solvent separated ion pair, with the leaving group that has departed from the β-face; **VII**: contact ion pair, with the leaving group associated at the β-face; **VIII**: reactive covalent β-intermediate; **IX**: addition product; LG = leaving group; P = protection group; E-X = promoter system; Nu = nucleophile.

The activation of a donor glycoside (**I**) leads to an array of reactive (electrophilic) intermediates (**II** – **VIII**), formed from the donor glycoside and the activator derived counterion. In case a participating group is present at the C2 (such as an *O*-acyl functionality) these reactive intermediates are intramolecularly trapped to provide a relatively stable dioxolenium ion, that is stereoselectively substituted from the opposite side of the ring to deliver the 1,2-*trans* glycoside product. In the absence of a C2-participation functionality, the situation is more complex and it has been proposed that both covalent reactive intermediates (**II** and **VIII**) and reactive oxocarbenium ion (like) species (**III** – **VII**) can be the product forming intermediates. The covalent intermediates on the S_N2-side of the reaction mechanism continuum can be studied using low-temperature NMR techniques and over the years hundreds of reactive intermediates (triflates, oxosulfonium ions, amongst others) have been characterized.[11–18] The substitution of these species with reactive nucleophiles (such as primary carbohydrate alcohols) defines the S_N2-side of the reaction mechanism continuum. In contrast, the oxocarbenium ions on the S_N1-side of the continuum remain ill-understood and the intermediacy of these species in glycosylation reactions is heavily debated.[19–36] Because the lifetime of these intermediates in conventional reaction media is extremely short, there is currently no (spectroscopic) technique available to study these species in a direct manner and assess their behavior.[37–39] It is clear that the substitution pattern on the carbohydrate ring plays an all-important role in determining the stability and reactivity of these species but it has been impossible to establish clear structure-reactivity-stereoselectivity relationships because of the conformational freedom and short life-time of these reactive intermediates in classical solutions. Thus, the course of S_N1-type glycosylation can at present not be properly understood (let alone predicted) leaving a major gap in the mechanistic conceptualization of glycosylation reactions.

To investigate the stability and reactivity of glycosyl oxocarbenium ions as product forming intermediates in glycosylation reactions, in this chapter the development of a computational method is reported that maps the stability of these species as a function of their overall shape. It is shown that the stereoselectivity of glycosylation reactions employing weak nucleophiles can be directly related to the conformational energy landscape (CEL) of the glycosyl oxocarbenium ions, as mapped *in silico*, and in doing so the S_N1-side of the glycosylation reaction mechanism continuum is defined. Direct spectroscopic evidence for the computed conformers is obtained by generation of the oxocarbenium ions under superacid conditions and it is revealed that fully substituted glycopyranosyl oxocarbenium ions react in a highly stereoselective 1,2-*cis* manner.

Results and discussion

The energy of glycopyranosyl oxocarbenium ions has been mapped as a function of their shape to understand the reactivity of these species following the strategy outlined in Figure 2. To generate the CEL maps, plotted on the Cremer-Pople sphere (a spherical representation describing all possible conformations a six-membered ring can adopt), a

suite of conformations was generated, by scanning the three dihedral angles (C1-C2-C3-C4, C3-C4-C5-O5, and C5-O5-C1-C2) from −60° to 60° in 15° increments, to fill the complete conformation space (Figure 2-1). The geometry of all these conformers was optimized and the associated energies computed by utilizing DFT as the level of theory, B3LYP as hybrid functional[40] and 6-311G(d,p) as the basis set. Solvation of CH_2Cl_2 was taken into account using a polarizable continuum model and energies are expressed in Gibbs free energy (For more information see Supplementary Information).[41] The energy landscapes were then generated by visualizing the relative energy in contour plots on "slices" of the pseudo rotational sphere.[42]

Inspection of the generated energy maps revealed that two families of structures are most relevant: the continuum of (^3E, $^3H_4$, E_4, and $B_{2,5}$)-like structures are grouped on the north-east side of the spheres and these form an ensemble of structures that are preferentially attacked from the top face. The 'opposite' family of structures, located on the south-west side of the sphere, is composed of the range of (^4E, $^4H_3$, E_3, and $^{2,5}B$)-like conformers, which are likely be approached by an incoming nucleophile from the bottom face (see Figure 2 and Supplementary Information).[20,43] The relative population of all conformational states can be calculated, based on their relative energies as computed above, utilizing the Boltzmann equation (see Supplementary for more information). Accordingly, the population of the top- and bottom face selective families was determined, which should be a measure for the relative stereoselectivity of addition reactions with weak nucleophiles to the glycosyl oxocarbenium ions.

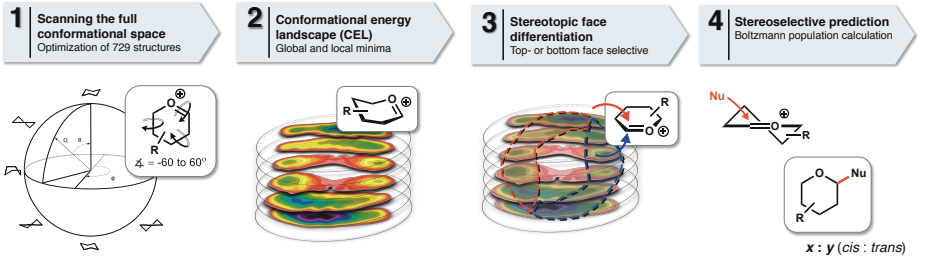


Figure 2. Overview of the workflow to map the conformational and stereoselective preference of pyranosyl oxocarbenium ions. (1) The complete conformational space of a six membered ring was scanned by computing 729 pre-fixed structures; A few canonical conformations (chair, half-chair, envelope and boat) are depicted; (2) The associated energies were graphed on slices dividing the Cremer-Pople sphere; (3) Top- and bottom face selective conformers lie in separate areas of the sphere. The family of top face-selective (^3E, $^3H_4$, E_4 and $B_{2,5}$)-like structures are found in the area contoured with the red dashed line, while the bottom face-selective family of (^4E, $^4H_3$, E_3, and $^{2,5}B$)-like conformers is found on the opposite side of the sphere, grouped within the blue dashed line; (4) Based on the Boltzmann distribution of the top- and bottom-face selective structures the stereochemical outcome of nucleophilic addition reactions to pyranosyl oxocarbenium ions can be computed.

To put this workflow to practice, a set of 13 mono-substituted pyranosyl oxocarbenium ions was investigated, differing in the nature of the substituent (BnO–, TBDPSO–, N_3–, F–, Cl–, Br–, I–, PhS–, MeS– and Me–) as well as the position on the ring. Their structures, the computed theoretical reaction stereoselectivity and the experimentally determined stereoselectivity obtained in reactions with classical S_N1-nucleophiles, triethylsilane-*d* (TES-*d*)[19,44–46] or allyltrimethyl silane (allyl-TMS), are summarized in Table 1 (Entry 1-13). The CEL maps (see Figure 3A for three representative examples, all other CEL maps are provided in Figures SI S3-S8) revealed that only a limited region of the full conformational space is accessible for the monosubstituted ions, in which local minima are found at both "poles", centered around the $^3H_4$- and the $^4H_3$-like conformations. Depending on the nature of the substituents, one of these families is favored, placing the substituent either axially or equatorially. At the C4-position, electronegative substituents (BnO–, F–, TBDPSO–, N_3–, Cl–, and Br–) favor an axial position to stabilize the oxocarbenium ion by through space electrostatic interactions, preferentially adopting the $^4H_3$-like conformation.[31,32,47–49] Decreasing electronegativity and increasing size of the substituent (I–, PhS–, MeS– and Me–) translates to a preference to adopt an equatorial position (*i.e.*, $^3H_4$-like conformations) to minimize steric interactions (Figure 3A). This trend is similar for substituents at the C3-position. An electronegative BnO-substituent at C2-position is preferentially placed in a *pseudo*-equatorial position as this enables the hyperconjugative stabilization of the oxocarbenium ion by the *pseudo*-axial C2-H2 bond. When the population of the conformational families, as revealed in the CEL maps, are translated to a calculated stereoselectivity and compared to the stereoselectivity obtained in the experiments[31,32,50] it becomes apparent that there is excellent agreement between theory and practice. Importantly, not only highly stereoselective glycosylations can be reliably predicted from the CEL maps, but also the condensation reactions that proceed with moderate selectivity (*e.g.*, Table 1, Entries 6, 7 and 13) are accurately matched by the computed data.

Next, CEL maps of multi-substituted pyranosyl oxocarbenium ions were generated and the theoretical stereoselectivity of these species computed. The results of these studies are summarized in the second half of Table 1 (Entry 14-32). A selection of CEL maps is depicted in Figure 3B (All CEL maps are provided in Figures SI S3-S9). Table 1 also reports the experimental stereoselectivity and yield of the reactions of the thioglycoside donors, obtained by pre-activation of the donors using the diphenyl sulfoxide (Ph_2SO)/triflic anhydride (Tf_2O) activator[51] and TES-*d* as the nucleophile.[52] Again, excellent agreement is found for the calculated and experimentally obtained stereoselectivity. The stereoselectivity of all these condensation reactions can now be traced back to the families of low-energy conformers of the oxocarbenium ions as revealed by the CEL maps. Some maps show a very localized energy minimum for a particular conformational family, such as the CEL map for the L-fucosyl oxocarbenium ion **19** (Figure 3B).

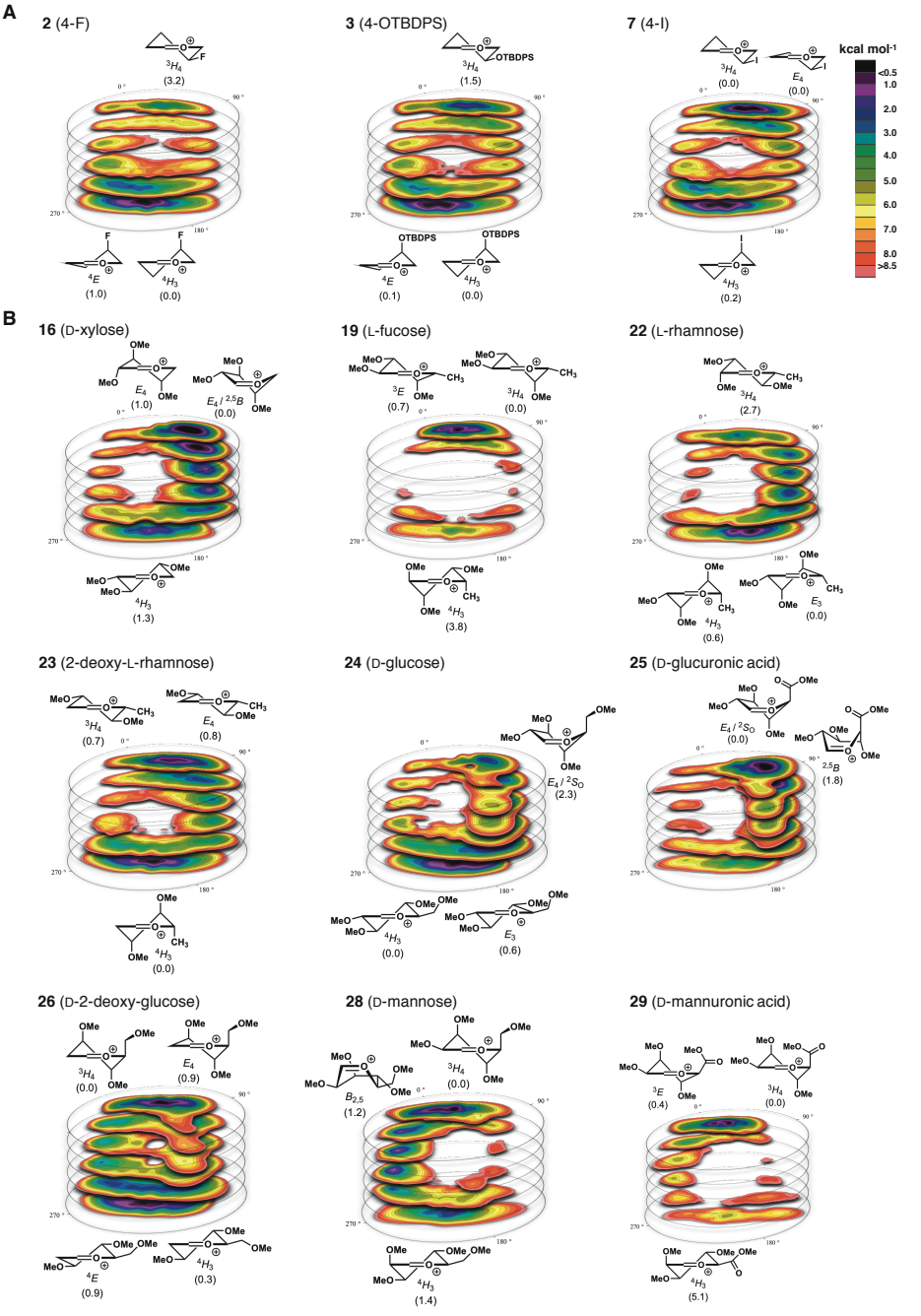


Figure 3. CEL maps of selected pyranosyl oxocarbenium ions in which the found local minima are indicated with their respective energy. (A) CEL map of mono-substituted-pyranosyl oxocarbenium ions **2**, **3** and **7**; (B) CEL map of multi-substituted-pyranosyl oxocarbenium ions **16**, **19**, **22**-**26** and **28**-**29**. All energies are computed at PCM(CH_2Cl_2)-B3LYP/6-311G(d,p) at T=213.15 K and expressed as solution-phase Gibbs free energy.

Table 1. Computed and experimentally found stereoselectivity for glycosylation reactions on mono- and multi-substituted pyranosyl oxocarbenium ions.[56] For the mono-substituted pyranosides (Entry 1-13) the *cis*:*trans* ratio is expressed as the relationship between the substituent and the coupled nucleophile; for the 2-deoxy-glycosides (Entry 17, 20, 23 and 32) the *cis*:*trans* ratio is expressed as the relationship between the substituent on C3-position and the coupled nucleophile; for the other glycopyranosides (Entry: 14-16, 18-19, 21-22 and 27-31) the *cis*:*trans* ratio is expressed as the relationship between the substituent on C2-position and the coupled nucleophile. The names in the table relate to the carbohydrate studied. For the computational studies, per-*O*-methylated oxocarbenium ions are used, where the experimental glycosylation use per-*O*-benzylated substrates.[57] Entries 1-13 are experimentally performed with allyl-TMS by the group Woerpel,[31,32] while Entries 14-32 are done with TES-*d*.

Entry	oxocarbenium ion	computed selectivity (*cis*:*trans*)	experimental selectivity (*cis*:*trans*)	yield (%)
1	**1** (4-OBn)	<2:98	<2:98	75
2	**2** (4-F)	<2:98	4:96	45
3	**3** (4-OTBDPS)	8:92	6:94	99
4	**4** (4-N_3)	12:88	12:88	95
5	**5** (4-Cl)	10:90	14:86	90
6	**6** (4-Br)	32:68	29:71	87
7	**7** (4-I)	73:27	72:28	90
8	**8** (4-SPh)	81:19	78:22	87
9	**9** (4-SMe)	88:12	84:16	75
10	**10** (4-Me)	95:5	94:6	74
11	**11** (3-OBn)	90:10	92:8	95
12	**12** (3-Me)	4:96	3:97	41
13	**13** (2-OBn)	66:34	66:34	85
14	**14** (D-lyxose)	>98:2	>98:2	81
15	**15** (D-arabinose)	>98:2	>98:2	79
16	**16** (D-xylose)	>98:2	>98:2	86
17	**17** (2-deoxy-D-xylose)	>98:2	>98:2	74
18	**18** (D-ribose)	>98:2	>98:2	69
19	**19** (L-fucose)	>98:2	>98:2	74
20	**20** (2-deoxy-L-fucose)	<2:98	<2:98	89
21	**21** (2-azido-L-fucose)	>98:2	>98:2	65
22	**22** (L-rhamnose)	>98:2	>98:2	79
23	**23** (2-deoxy-L-rhamnose)	71:29	66:34	96
24	**24** (D-glucose)	>98:2	>98:2	70
25	**25** (D-glucuronic acid)	>98:2	>98:2	43
26	**26** (2-deoxy-D-glucose)	52:48	52:48	76
27	**27** (2-azido-D-glucose)	>98:2	>98:2	52
28	**28** (D-mannose)	97:3	97:3	93
29	**29** (D-mannuronic-acid)	>98:2	>98:2	76
30	**30** (2-azido-D-mannuronic-acid)	>98:2	>98:2	53
31	**31** (D-galactose)	>98:2	>98:2	86
32	**32** (2-deoxy-D-galactose)	<2:98	<2:98	91

In the most favorable $^{3}H_{4}$-, ^{3}E- and E_{4}-like conformations of this ion, the ring substituents at C2 and C4 take up an electronically favorable orientation, leading to the localized energy minimum around the $^{3}H_{4}$-pole. Nucleophilic addition to these conformers stereoselectivity provides the 1,2-*cis*-linked products and the generated CEL map thus provides an explanation for the high 1,2-*cis*-selectivity generally observed with fucosyl donors.[53–55]

Similarly, the mannosyl oxocarbenium ion **28** can place its C2, C3 and C4 substituents in stabilizing positions when adopting a $^{3}H_{4}/^{3}E$-like structure (Figure 3B) as alluded to by Woerpel and co-workers.[24] These structures are selectively substituted from the top face to provide the β-mannosyl product, a result that is indeed born out in the glycosylation experiment (Table 1, Entry 28). Glycosylations of mannuronic acid ester **29** proceed with exceptional 1,2-*cis* stereoselectivity and the generated CEL map (Figure 3B) provides an adequate explanation for this reaction outcome as a very localized energy minimum is determined for the $^{3}H_{4}$-like conformational family. The additional stabilization from the axial C5-CO_2Me in **29** with respect to the axial C5-CH_2OMe group in the mannosyl oxocarbenium ion (**28**) becomes very clear from the comparison of the CEL maps of **28** and **29**.

The CEL maps of pyranosyl oxocarbenium ions bearing substituents, that have "conflicting positional interests" reveal that non-canonical conformations can become important and that broader conformational families or families around the different poles can become equally relevant. For example, the D-xylosyl oxocarbenium ion **16** preferentially adopts a non-canonical flattened (skew)-boat-like structure (see Figure 3B). The CEL map for the 2-deoxy-L-rhamnose ion **23** reveals two conformational families of similar energy, leading to a mixture of α- and β-products in the condensation reaction (Table 1, Entry 23). The CEL maps in the *gluco*-series illustrate how point mutations in the structure of the parent donor translate to differently shaped oxocarbenium ions and a different stereochemical outcome in the glycosylation reactions. The glucopyranosyl cation **24** is most stable when adopting a $^{4}H_{3}/E_{3}$-like shape, while its glucuronic acid counterpart (**25**), bearing a C5-carboxylic acid ester prefers to adopt a structure in between the $E_{4}/^{2}S_{O}$-conformations. Both ions are preferentially attacked from the bottom face to selectively provide the α-product (Table 1, Entry 24 and 25). For 2-deoxyglucose **26**, two families of oxocarbenium ion conformers are equally stable and the populations of $^{4}H_{3}/^{4}E$-like and $^{3}H_{4}/E_{4}$-like states point to an unselective addition reaction leading to the formation of α- and β-products in almost equal amounts. Overall, there is excellent agreement between the calculated and experimentally established α/β-selectivity of the multi-substituted glycosides, providing very compelling evidence for (families of) glycopyranosyl oxocarbenium ion conformers as product forming intermediates in the substitution reactions, thereby defining the S_N1-side of the glycosylation reaction mechanism manifold.

To obtain direct experimental support for the conformations computed using the CEL mapping method two 2-deoxy diacetylated oxocarbenium ions derived from L-fucose **33** and L-rhamnose **34** were studied in "non-nucleophilic" super acidic media (Figure 4A).[37]

The choice of acetyl groups and a 2-deoxy position is guided by the fact that methoxy groups are prone to elimination and the presence of a C2-substituent results in by-products. As the acetyl groups at C3- and C4-position of the oxocarbenium ions generated from donors **33** and **34** will be protonated under the superacid conditions used, polycationic oxocarbenium ions **35** and **36** were subjected to the CEL mapping method. The CEL map for 2-deoxy-fucosyl oxocarbenium ion **35** (Figure 4C) shows a strong preference for the $^3H_4$ and closely related E_4 conformations. The CEL map for the 2-deoxy-rhamnosyl oxocarbenium ion **36**, on the other hand, features multiple local minima and both the $^3H_4$ and the $^4H_3$-family are relatively low in energy resulting in a conformational mixture in solution. In parallel, 2-deoxy-L-fucose and 2-deoxy-L-rhamnose acetates **33** and **34** were dissolved in HF/SbF_5 to generate the polycationic structures **35** and **36**, of which the NMR spectra (Figure 4B) clearly indicated the presence of an oxocarbenium ion as the main species (carboxonium signal **35**: δ_{C1} = 224.2 ppm and δ_{H1} = 8.76 ppm; **36**: δ_{C1} = 223.4 ppm and δ_{H1} = 8.84 ppm).[37,58]

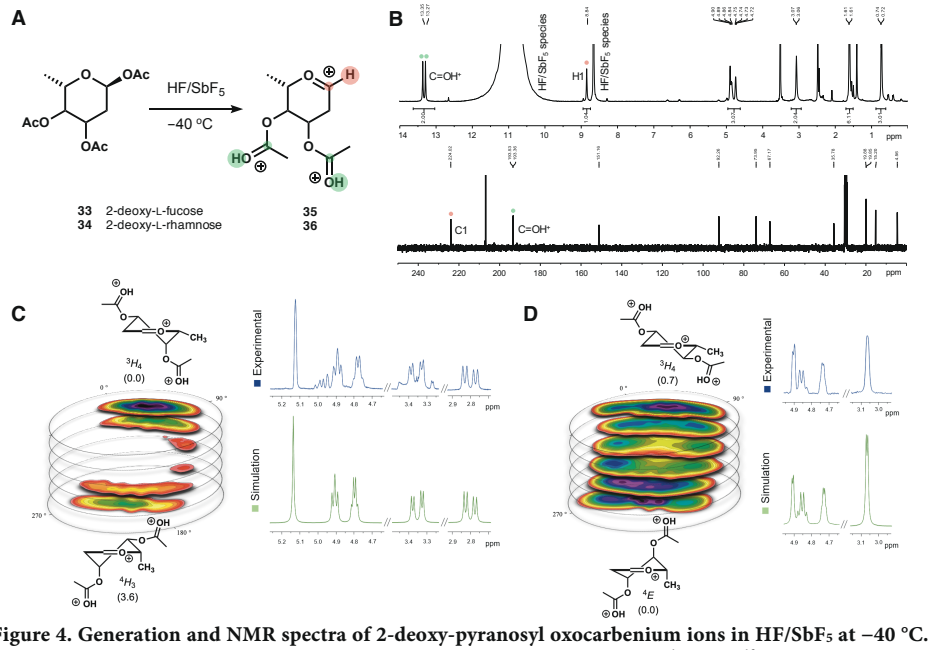


Figure 4. Generation and NMR spectra of 2-deoxy-pyranosyl oxocarbenium ions in HF/SbF_5 at −40 °C. (A) Generation of oxocarbenium ion **35** and **36** in HF/SbF_5; (B) Experimental ^{1}H- and ^{13}C DEPT NMR of 2-deoxy-L-rhamnose oxocarbenium **36**; (C) The generated ^{1}H-NMR spectrum of the oxocarbenium **35** compared to the simulated spectrum based on the computed CEL; (D) The generated ^{1}H-NMR spectrum of the oxocarbenium **36** compared to the simulated spectrum based on the computed CEL.

Both ester groups were indeed protonated as revealed by the presence of two proton singlets at δ_H = 13.28 ppm and 13.35 ppm). Because of the sufficient lifespan of **35** and **36** in the superacid media, full conformational characterization of these species could be

performed (see SI for more information). The coupling constants of the ring protons of **35** indicate that it adopts a $^{3}H_{4}$-like conformation. The NMR spectrum of 2-deoxy-L-rhamnosyl oxocarbenium **36** (Figure 4D) on the other hand showed significant line broadening as a result of the conformational flexibility of this species. Using the relevant conformations, obtained from the CEL maps for these ions, the NMR spectrum was reconstituted using the Boltzmann weighted averaged coupling constants of ions **35** and **36**. Perfect agreement between the experimental NMR spectra for these per-*O*-acetylated polyprotonated glycosyl cations and their simulated spectra show that the conformational dynamics of these ions are well captured by the CEL mapping method.

Conclusion

In conclusion, this chapter has benchmarked the S_N1-side of the glycosylation reaction mechanism. The stability, reactivity and conformational mobility of glycosyl oxocarbenium ions can be fully understood by mapping the complete conformational energy landscape of these ions and the preference of the cations can be directly related to the experimental stereochemical outcome of addition reactions to these. The maps show in detail how the stereoelectronic effects of various ring substituents (halogens, chalcogens, azides, and carbon-based substituents) determine the overall shape of the cations and thereby the stereochemical course of the reactions. In addition, the simulated NMR spectra of selected ions, reconstituted by using the Boltzmann weighted averaged coupling constants determined by the CEL mapping method, perfectly fit with the experimental ones observed by low-temperature NMR in superacid. Where glycosyl oxocarbenium ions were previously thought to be at the basis of non-selective coupling reactions because of their high reactivity, this chapter shows that these species – including the ions derived from L-fucose, L-rhamnose, D-glucose, D-mannose and D-galactose – have an intrinsic preference to generate the challenging 1,2-*cis*-linkages. This will enable the stereoselective synthesis of *C*-glycosides and open up new avenues to develop stereoselective *O*-glycosylation reactions.[59] The mechanistic insight offered here will be instrumental in the interpretation of future glycosylation results and serve as the basis to further explore the glycosylation reaction mechanism. The uncovered stereoelectronic substituent effects will be relevant in many other transformations involving carbocationic intermediates, and the strategy developed to grasp the full conformational space of these flexible intermediates can be a blueprint for the study of other flexible reactive intermediates.

Supporting information

DFT calculations

General procedure I: conformational energy landscape calculation of glycosyl cations • To keep the calculation time manageable, the *O*-Bn protection groups were substituted with electronically comparable smaller groups (*i.e.*, *O*-Me). The initial structure for the conformational energy landscape (CEL) was optimized by starting from a 'conformer distribution search' option included in the Spartan 10 program by utilizing DFT as the level of theory and the hybrid functional B3LYP in gas phase with 6-31G(d) as the basis set. All generated gas-phase geometries were re-optimized with Gaussian 09 rev D.01 by using B3LYP/6-311G(d,p), after which a vibrational analysis was computed to obtain the thermodynamic properties. The gas-phase structures were then solvated by using the PCM implicit solvation model, with CH_2Cl_2 as solvent (or in selected cases Et_2O or MeCN). Solvent effects were explicitly used in solving the SCF equations and during the optimization of the geometry. For heavy elements, including iodine, a combination of LANL2DZ and 6-311G(d,p) was used as basis set by utilizing the keyword "genecp". The geometry with the lowest solvated energy was selected as the starting point for the CEL map. A complete survey of the possible conformational space was done by scanning three dihedral angles ranging from –60° to 60°, including the C1-C2-C3-C4 (D1), C3-C4-C5-O (D3) and C5-O-C1-C2 (D5). The resolution of this survey is determined by the step size which was set to 15° per puckering parameter, giving a total of 729 pre-fixed conformations per six-membered oxocarbenium ion spanning the entire conformational landscape. All other internal coordinates were unconstrained. With the exception of a C2-substituent being present on the oxocarbenium ring of interest, then the C2-H2 bond length was fixed based on the optimized structure to counteract rearrangements occurring for higher energy conformers. The 729 structures were computed with Gaussian 09 rev D.01 again with a two-step procedure. First, the structures were optimized in the gas-phase with B3LYP/6-311G(d,p), after which a vibrational analysis was computed to obtain the thermodynamic properties. The gas-phase structures were then solvated by using the PCM implicit solvation model, with CH_2Cl_2 as solvent (or in selected cases Et_2O or MeCN). Solvent effects were explicitly used in solving the SCF equations and during the optimization of the geometry. For pyranosyl oxocarbenium ions bearing a C5-C6 substituent, three staggered rotamers (*i.e.*, *gg*, *gt*, *tg*) of the O5-C5-C6-O6 dihedral angle (*i.e.*, –65°, 65°, 175°) were considered. Earlier work showed the importance of these rotamers and their crucial impact on the selectivity and reactivity of the ion.[60] The CEL maps were computed separately and the starting geometry was obtained from the method described above in which the lowest, ZPE corrected, solvated energy generated rotamers were used. The three C5-C6 bond rotamers (not constrained) bring the total conformations for each pyranosyl oxocarbenium ion configuration to 2187 geometries. The final denoted free Gibbs energy was calculated using Equation S1 in which ΔE_{gas} is the gas-phase energy (electronic energy), $\Delta G^{T}_{gas,QH}$ (T = reaction temperature and p = 1 atm.) is the sum of corrections from the electronic energy to free Gibbs energy in the quasi-harmonic oscillator approximation also including zero-point energy (ZPE), and ΔG_{solv} is their corresponding free solvation Gibbs energy. The $\Delta G^{T}_{gas,QH}$ were computed using the quasi-harmonic approximation in the gas phase according to the work of Truhlar.[61]

$$\Delta G^{T}_{CH_2Cl_2} = \Delta E_{gas} + \Delta G^{T}_{gas,QH} + \Delta G_{solv} \qquad \text{(Eq. S1)}$$

$$= \Delta G^{T}_{gas} + \Delta G_{solv}$$

The quasi-harmonic approximation is the same as the harmonic oscillator approximation except that vibrational frequencies lower than 100 cm^{-1} were raised to 100 cm^{-1} as a way to correct for the breakdown of the harmonic oscillator model for the free energies of low-frequency vibrational modes. All optimized structures were checked for the absence of imaginary frequencies. To visualize the energy levels of the conformers on the Cremer-Pople sphere, slices were generated dissecting the sphere that combine closely associated conformers (Figure S1). The OriginPro software was employed to produce the energy heat maps, contoured at 0.5 kcal mol^{-1}. For ease of visualization, the Cremer-Pople globe is turned 180° with respect to its common representation and both poles (*i.e.*, the $^4C_1$ and $^1C_4$ structures) are omitted as these conformations are very high in energy. Visualization of conformations of interest was done with CYLview.

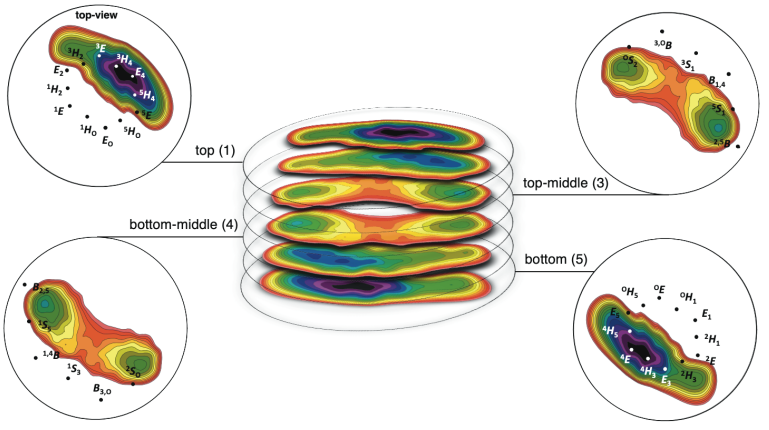


Figure S1. "Deconvolution" of the CEL map showing a top view of the most important slices that have been combined to generate the full CEL map.

General procedure II: stereochemical preference based on the computed CEL • To convert the relative energies of the continuum of conformers into the stereoselectivity of reactions the Boltzmann equation was used (Equation S2). The temperature used in the Boltzmann equation was equal to the reaction temperature. Inspection of the generated conformational energy maps led to the realization that two families of structures are most relevant: the continuum of (^3E, $^3H_4$, E_4 and $B_{2,5}$)-like structures and the 'opposite' family of structures, composed of the range of (E_3, $^4H_3$, ^4E and $^{2,5}B$)-like conformers.

$$\frac{N_i}{N_{total}} = \frac{e^{-E_{rel}/RT}}{\sum_{k=1}^{N_{total}} e^{-E_k/RT}} \qquad \text{(Eq. S2)}$$

To discriminate both families, a selection criterion was set to separate both conformational families. This selection was based on the H2$_{a/b}$-C2-C1-O5 dihedral angle of the oxocarbenium of interest (Figure S2). For the top-half of the CEL map, conformations with an H2$_a$-C2-C1-O5 angle larger than 105° were regarded as top face-selective, while a smaller angle was considered as bottom face-selective and vice versa for the bottom of the CEL map, but with the H2$_b$-C2-C1-O5 dihedral angle. This yields a top face- and bottom face-selective group with a corresponding fractional population, which was considered as the computed stereoselectivity of the computed oxocarbenium. Only calculated structures with a relative energy of < 5 kcal mol^{-1} were taken into account for calculating the Boltzmann distribution.

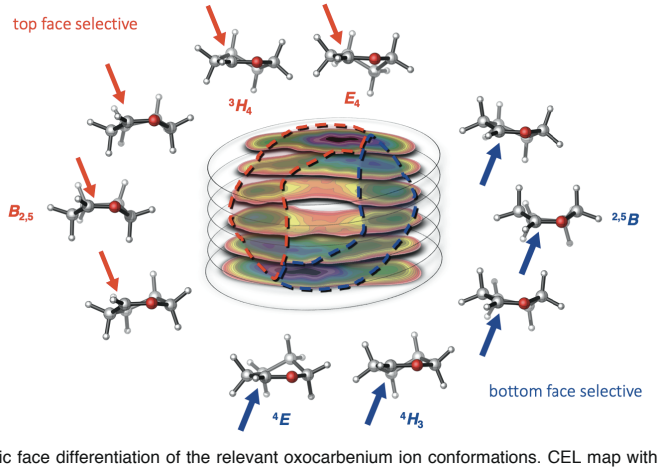


Figure S2. Stereotopic face differentiation of the relevant oxocarbenium ion conformations. CEL map with marked areas for the top- and bottom face-selective family of conformations.

General procedure III: simulation of NMR spectra based on the computed CEL map • To convert the relative energies of the continuum of conformers into simulated NMR spectra the Boltzmann equation was used (Equation S2). Based on all relevant geometries ($\Delta G^{T}_{gas/solution}$ < 2 kcal mol^{-1}) the spin-spin coupling constants were calculated according to the work of Rablen and Bally with the use of 6-311g(d,p) u+1s as basis set and a scaling factor of 0.92.[62] The computed total nuclear spin-spin coupling terms were used as calculated spin-spin coupling constants. Spectra were simulated with the use of MestReNova 9 with a line width of 4.0 Hz. The used chemical shift in the simulated spectra was acquired from the experimental spectra.

CEL maps • All CEL maps that are described in this chapter are summarized in the following section. The displayed CEL maps are based on the $\Delta G^{T}_{gas/solution}$ and relevant structures are added with their respective relative energy.

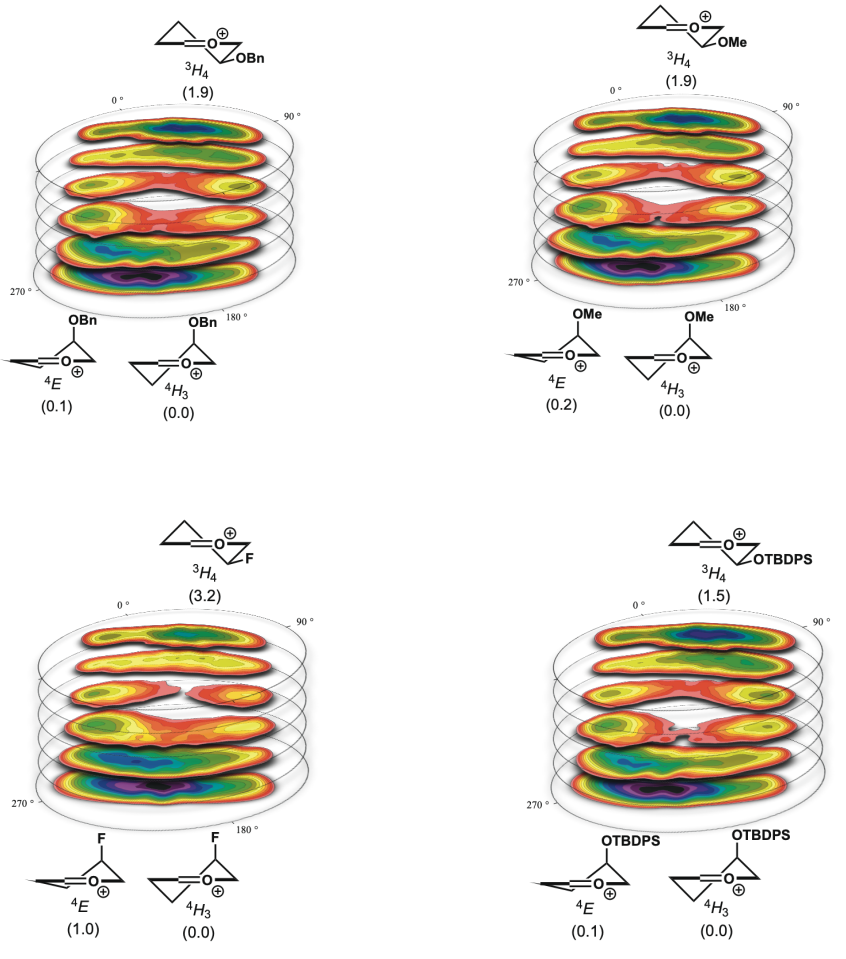


Figure S3. CEL maps of **1**, **S1**, **2** and **3**.

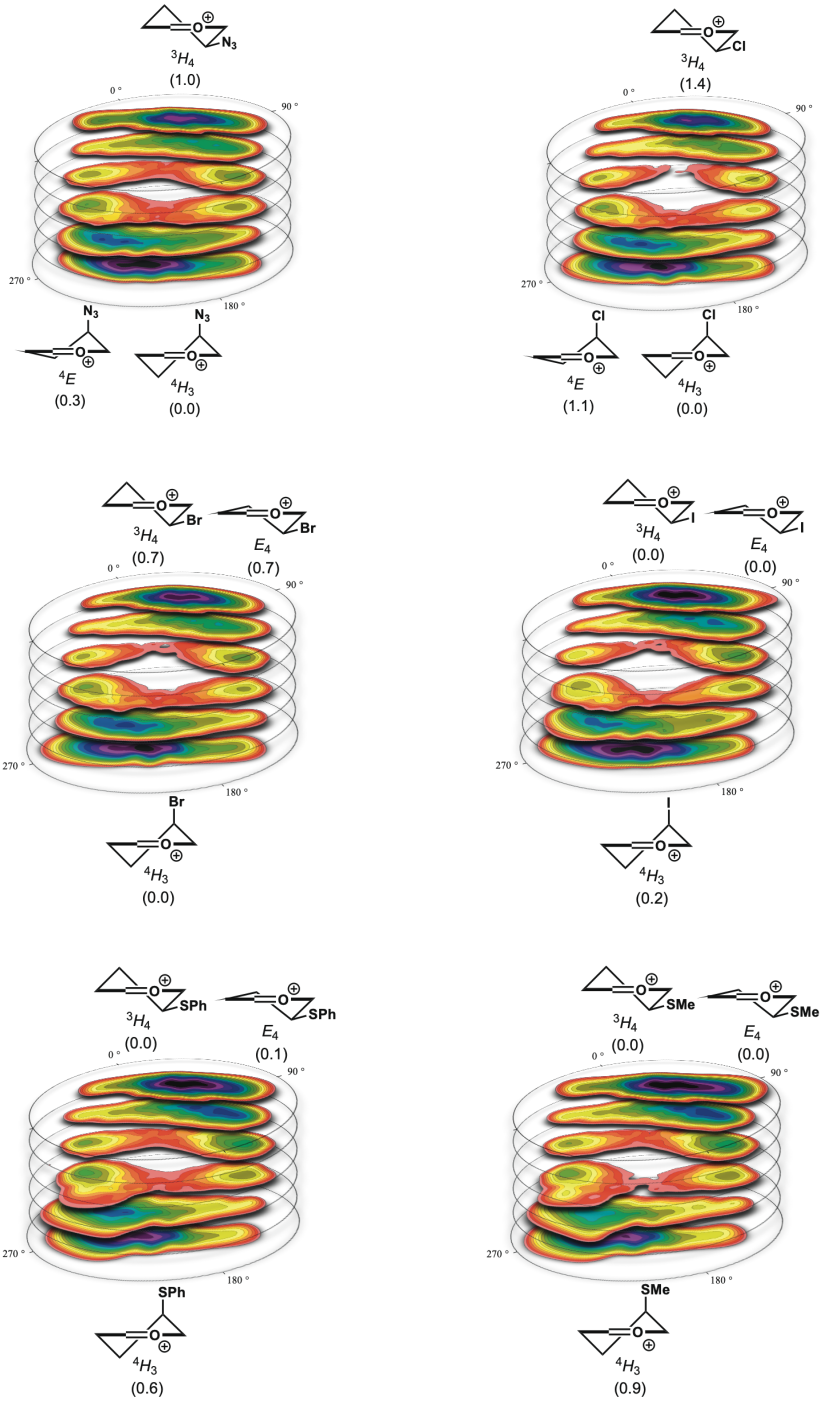


Figure S4. CEL maps of **4**, **5**, **6**, **7**, **8** and **9**.

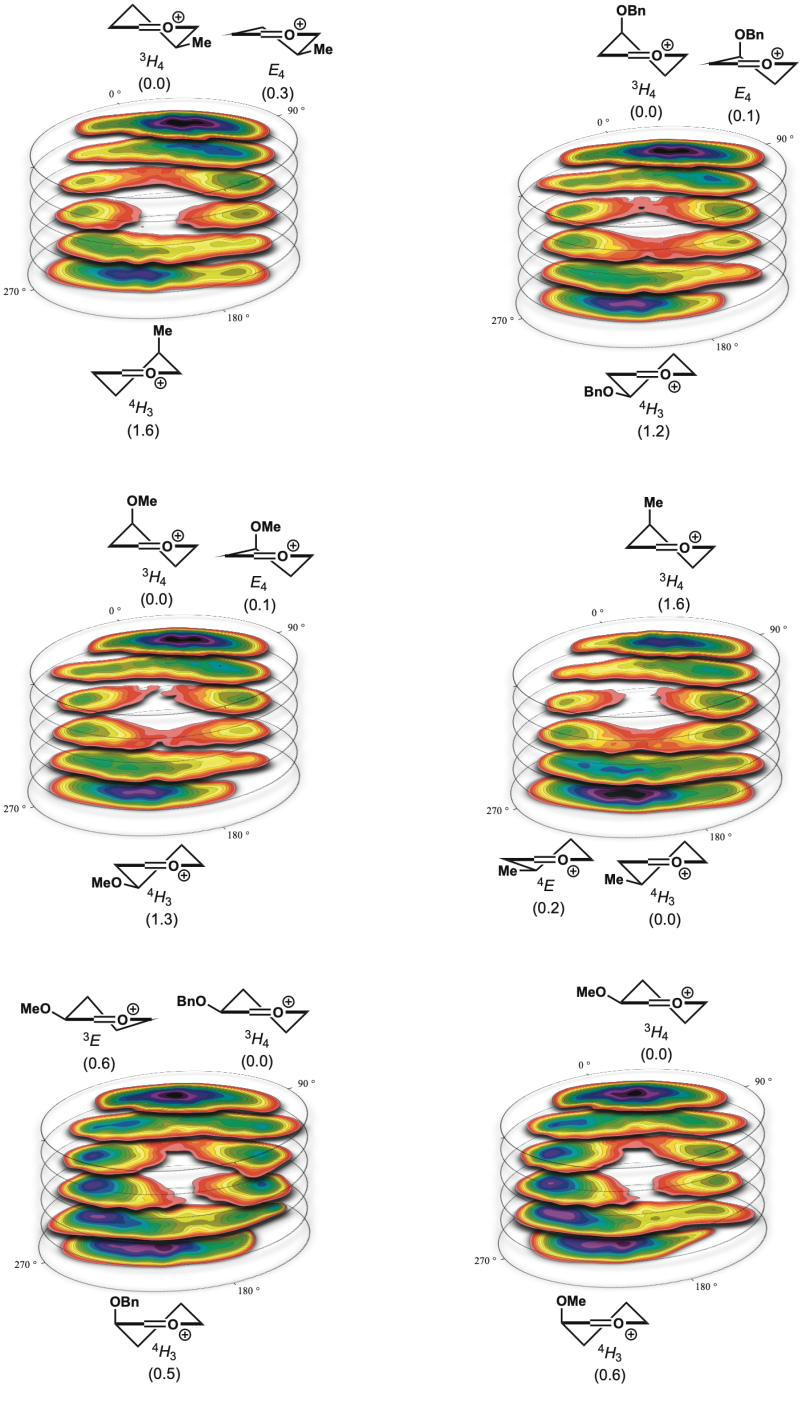


Figure S5. CEL maps of **10**, **11**, **S2**, **12**, **13** and **S3**.

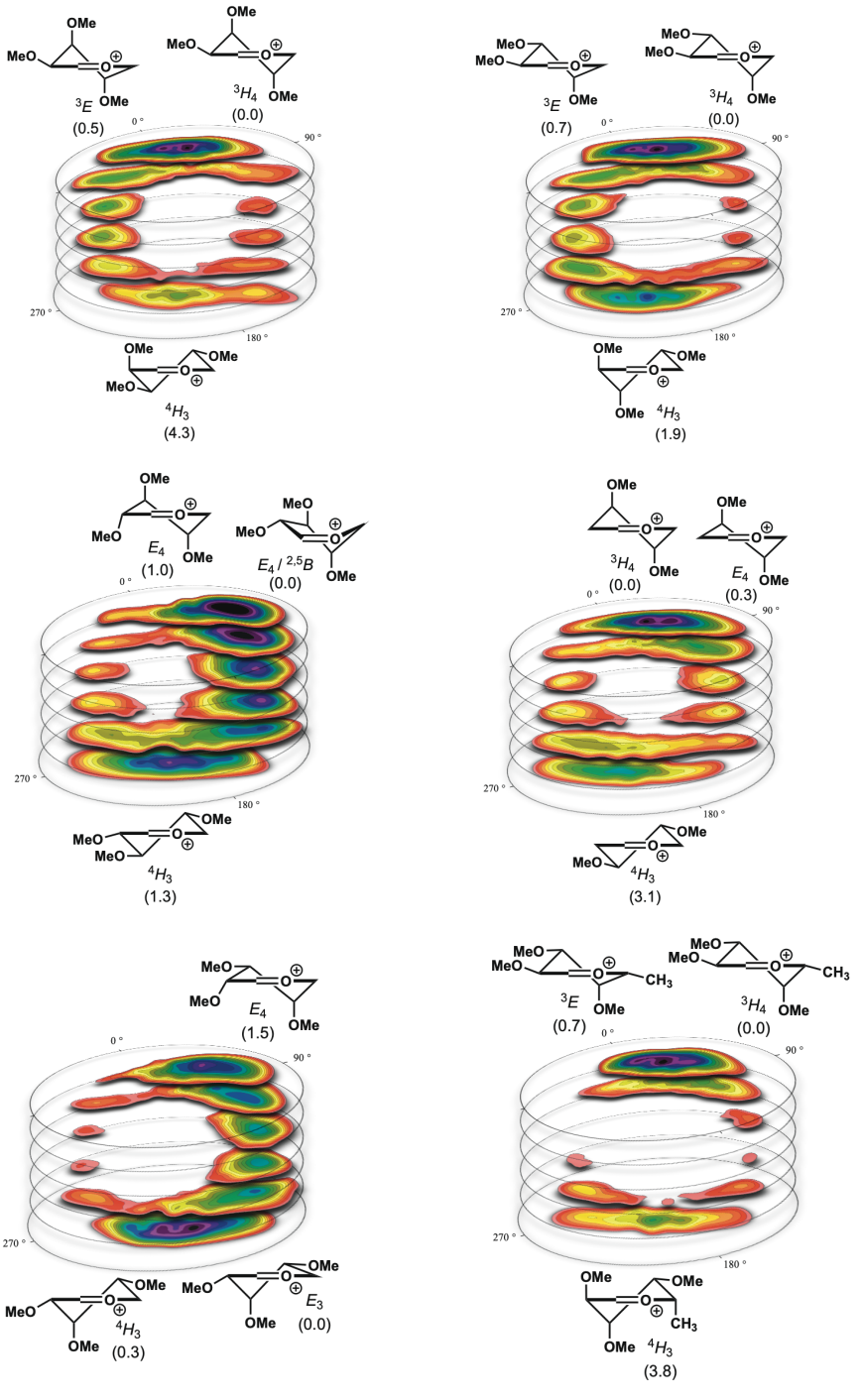


Figure S6. CEL maps of **14**, **15**, **16**, **17**, **18** and **19**.

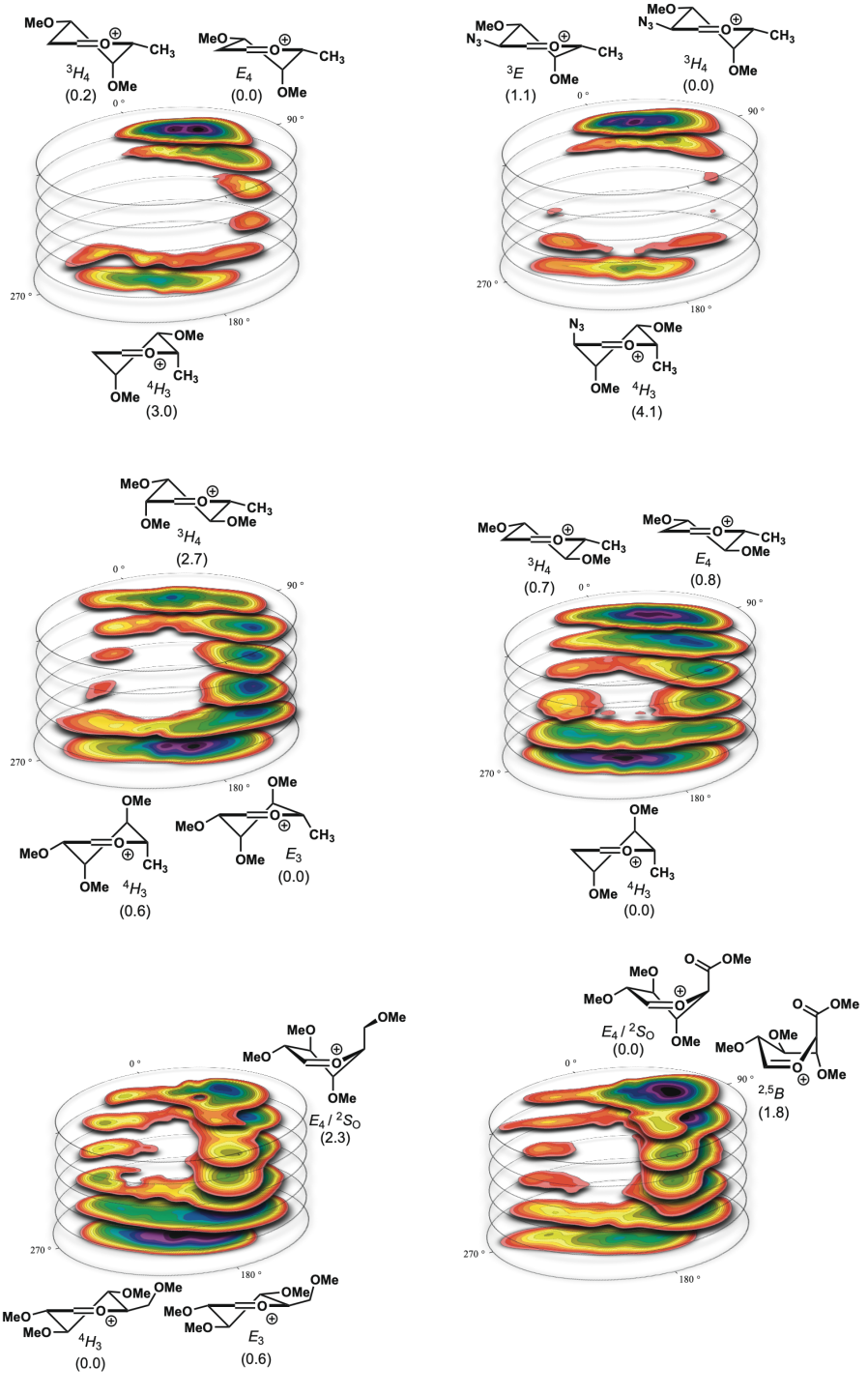


Figure S7. CEL maps of **20**, **21**, **22**, **23**, **24** and **25**.

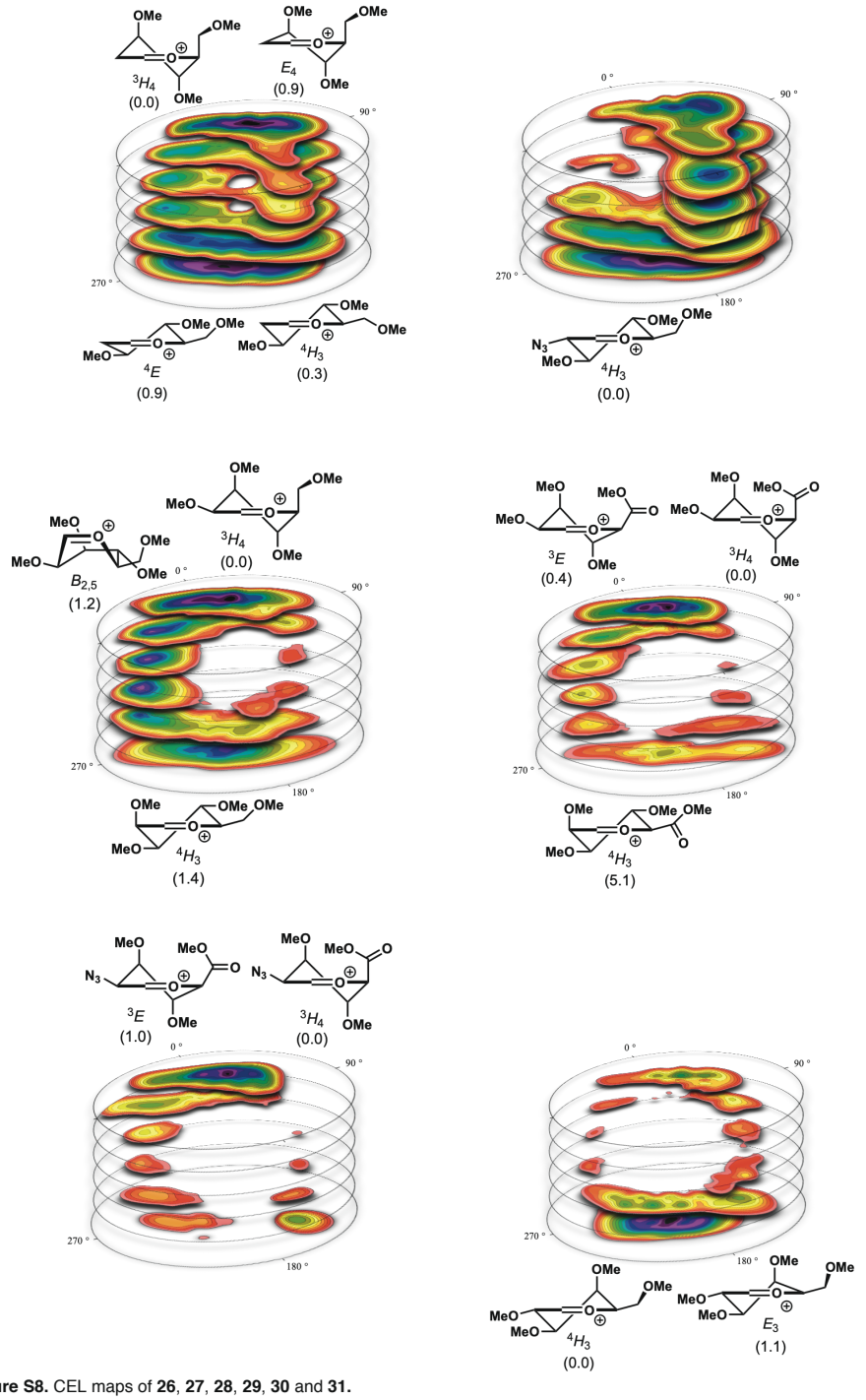


Figure S8. CEL maps of **26**, **27**, **28**, **29**, **30** and **31.**

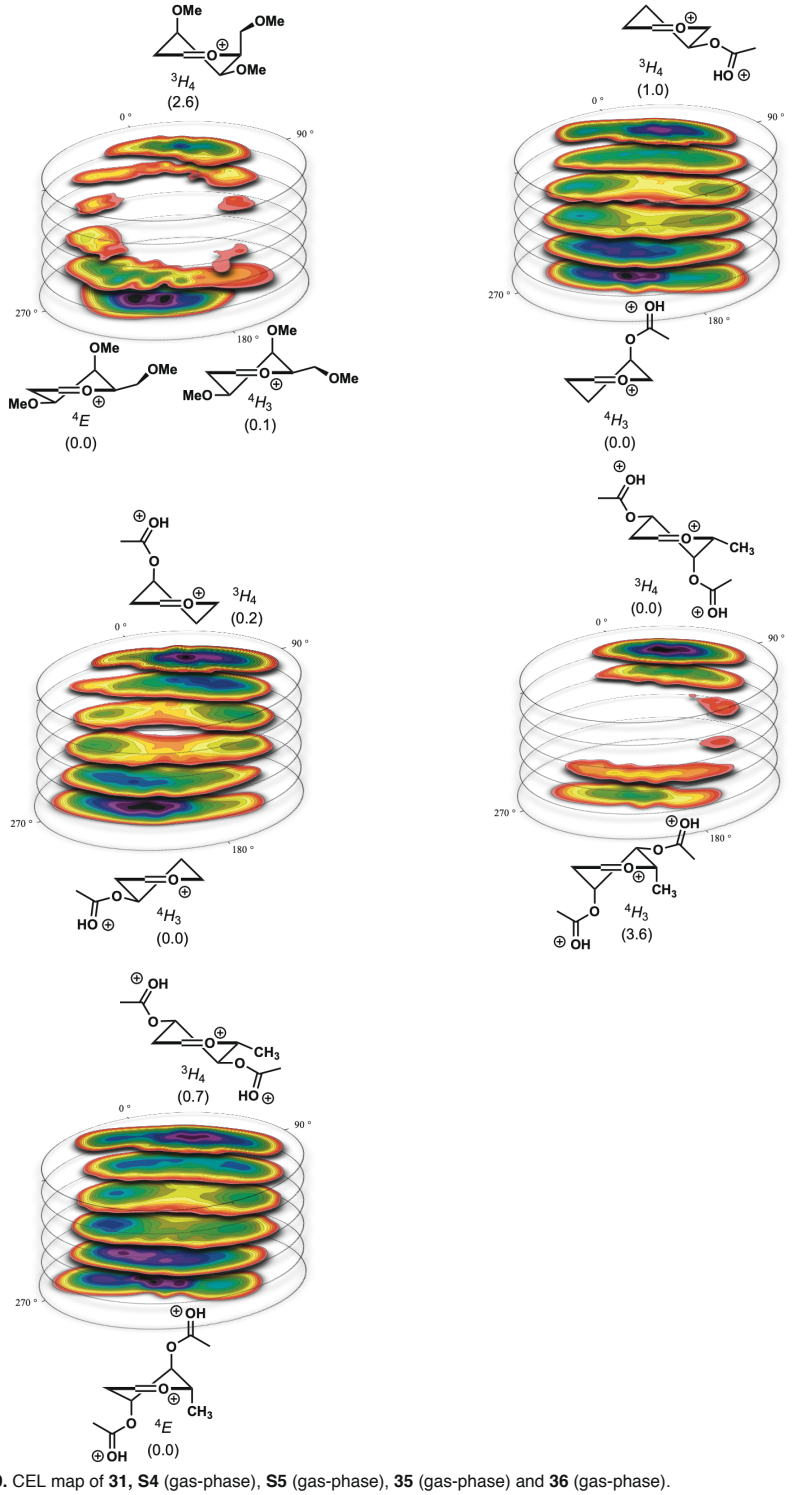


Figure S9. CEL map of **31, S4** (gas-phase), **S5** (gas-phase), **35** (gas-phase) and **36** (gas-phase).

Influence of the substituent orientation on the oxocarbenium ion stability • To investigate whether the orientation of the substitutions on the ring has an effect on the stability of the oxocarbenium ion, DFT computations were done in which the dihedral angle of the substituent was systematically rotated (Figure S10). Two important conformations were selected as starting point, including the $^{3}H_{4}$ and $^{4}H_{3}$, obtained from CEL maps. The ring dihedral angles were fixed to counter any conformational changes and the dihedral angle of interest was rotated from 0−360° with increments of 20°. All calculations were performed with Gaussian 09 rev. D.01 by using PCM(CH_2Cl_2)-B3LYP/6-311G(d,p).

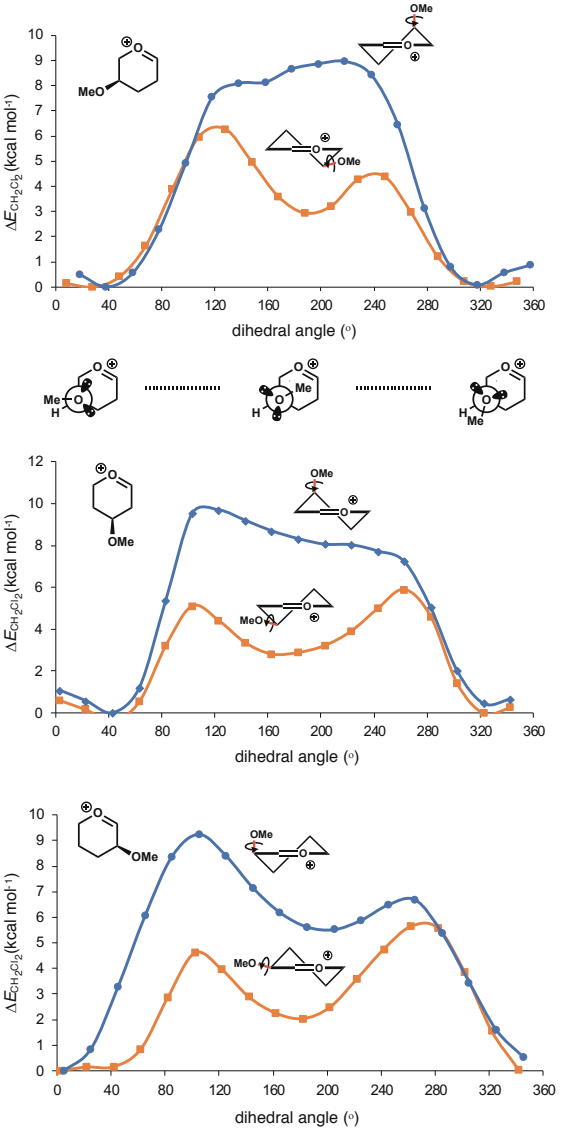
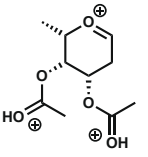


Figure S10. Probing the influence of the orientation of the C4-, C3- and C2-OMe substituent on the oxocarbenium ion stability. Energies are expressed as $\Delta E_{CH_2Cl_2}$; blue line = $^{4}H_{3}$ and orange line = $^{3}H_{4}$.

Superacid NMR experiments

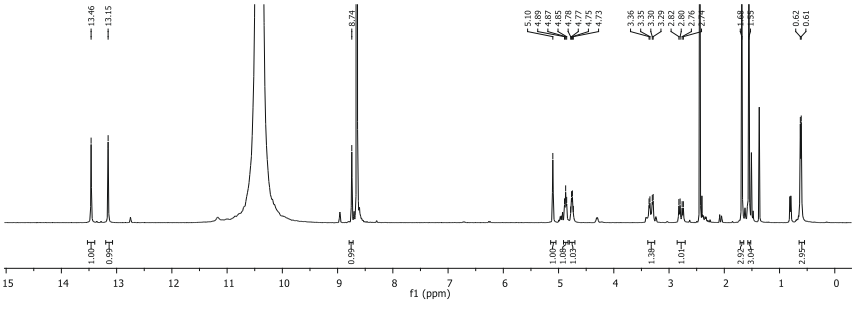
General procedure IV: NMR experiments in super acidic media • The authors want to draw the reader's attention to the dangerous features of super acidic chemistry. Handling of hydrogen fluoride and antimony pentafluoride must be done by experienced chemists with all the necessary safety arrangements in place. Experiments performed in superacid were carried out in a sealed Teflon® flask with a magnetic stirrer. No further precautions have to be taken to prevent reaction mixture from moisture (test reaction performed in anhydrous conditions leads to the same results). ^{1}H and ^{13}C NMR were recorded on a 400 MHz Bruker Advance DPX spectrometer using CD_3COCD_3 as an external reference. To get better resolution of signals with small coupling constants or overlapping signals a gaussian window function (LB = ± −1 and GB = ± 0.5) was used on the ^{1}H NMR spectrum. COSY and HSQC experiments were used to confirm the NMR peak assignments. To a magnetically stirred mixture of HF/SbF_5 (1 mL, SbF_5 22 mol%) maintained at −40 °C, was added substrate. After 5 min, the mixture was introduced in a Teflon® NMR tube which was inserted into a classical glass NMR tube containing acetone-d_6 as external standard.

Protonated pyranosyl oxocarbenium ions

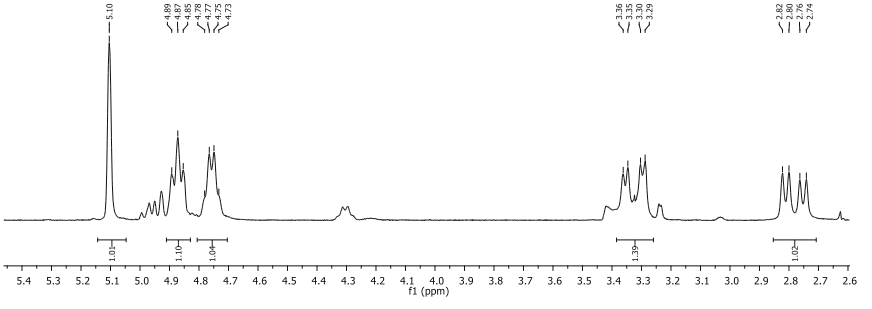


Protonated 2-deoxy-3,4-di-*O*-acetyl-fucose-L-pyranosyl oxocarbenium ion (35). The ion **35** was obtained from glycosyl donor **33** according to general procedure IV. ^{1}H NMR (400 MHz, Acetone-d_6): δ 13.46 (s, 1H, H'), 13.15 (s, 1H, H'), 8.74 (s, 1H, H-1), 5.10 (d, J = 3.0 Hz, H-4), 4.87 (t, J = 8.5 Hz, 1H, H-3), 4.76 (q, J = 6.4 Hz, 1H, H-5), 3.33 (dd, J = 23.7, 6.8 Hz, 1H, H-2b), 2.78 (dd, J = 23.7, 9.8 Hz, 1H, H-2a), 1.68 (s, 3H, CH_3Ac), 1.55 (s, 3H, CH_3 Ac), 0.62 (d, J = 6.5 Hz, 3H, CH_3); ^{13}C NMR (100 MHz, Acetone-d_6): δ 224.8 (CH, C-1), 194.2 (C=O), 193.3 (C=O), 94.7 (CH, C-5), 75.8 (CH, C-4), 69.6 (CH, C-3), 35.6 (CH_2, C-2), 19.6 (CH_3 Ac), 19.5 (CH_3 Ac), 13.0 (CH_3).

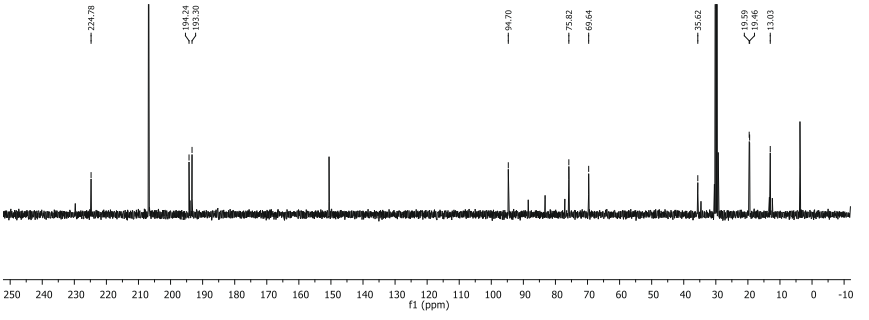
^{1}H NMR, acetone-d_6 of oxocarbenium ion **35**



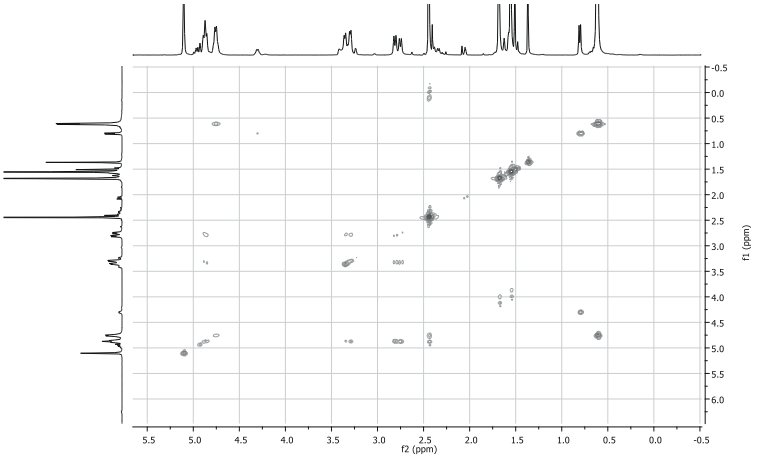
^{1}H NMR, acetone-d_6 of oxocarbenium ion **35** (cropped)



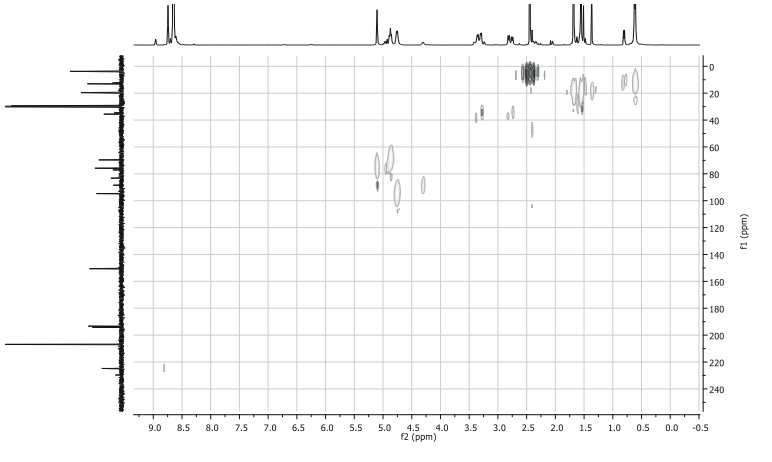
^{13}C NMR, acetone-d_6 of oxocarbenium ion **35**

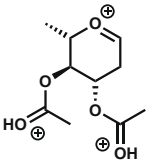


COSY NMR, acetone-d_6 of oxocarbenium ion **35**



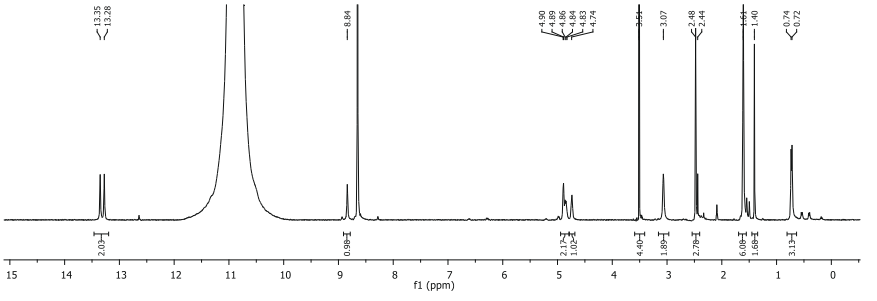
HSQC NMR, acetone-d_6 of oxocarbenium ion **35**



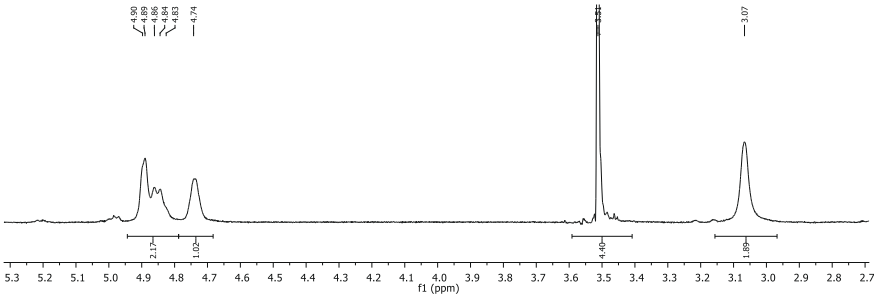


Protonated 2-deoxy-3,4-di-*O*-acetyl-rhamnose-L-pyranosyl oxocarbenium ion (36). The ion **36** was obtained from glycosyl donor **34** according to general procedure IV. ^{1}H NMR (400 MHz, Acetone-d_6): δ 13.35 (s, 1H, H'), 13.28 (s, 1H, H'), 8.84 (s, 1H, H-1), 4.89 (d, J = 3.5 Hz, 1H, H-4), 4.85 (q, J = 7.5 Hz, 1H H-5), 4.74 (bs, 1H, H-3), 3.07 (bs, 2H, H-2), 1.61 (s, 6H, 2x CH_3 Ac), 0.73 (d, J = 6.8 Hz, 3H, CH_3); ^{13}C NMR (100 MHz, Acetone-d_6): δ 224.0 (CH, C-1), 193.5 (C=O), 193.4 (C=O), 92.3 (CH, C-5), 73.5 (CH, C-4), 61.2 (CH, C-3), 35.8 (CH_2, C-2), 19.9 (CH_3 Ac), 19.8 (CH_3 Ac), 15.2 (CH_3).

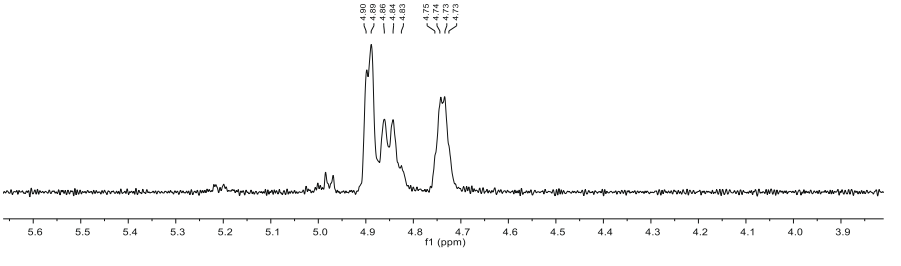
^{1}H NMR, acetone-d_6 of oxocarbenium ion **36**



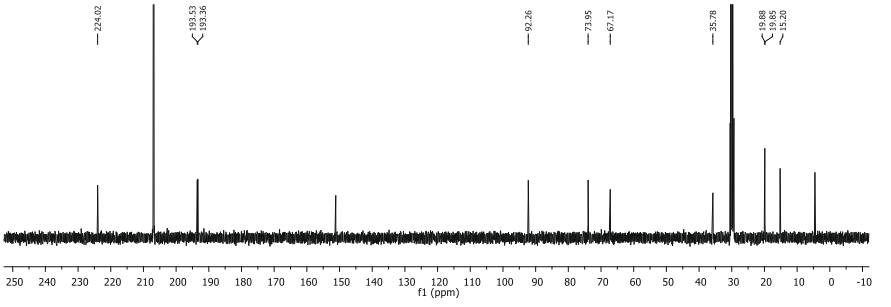
^{1}H NMR, acetone-d_6 of oxocarbenium ion **36** (cropped)



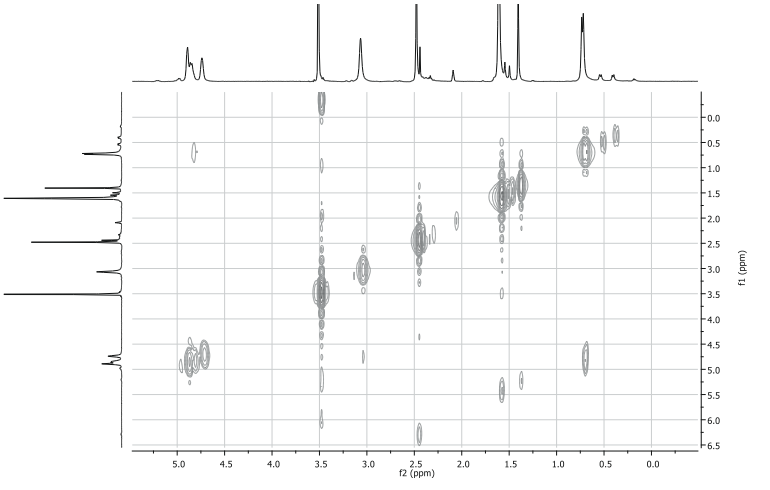
^{1}H NMR, acetone-d_6 of oxocarbenium ion **36** (cropped; LB = ± –2 and GB = ± 4)



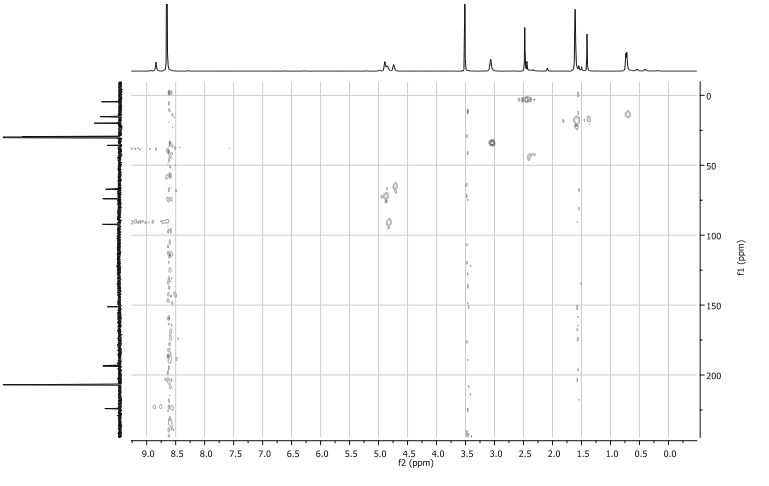
^{13}C NMR, acetone-d_6 of oxocarbenium ion **36**



COSY NMR, acetone-d_6 of oxocarbenium ion **36**



HSQC NMR, acetone-d_6 of oxocarbenium ion **36**



Organic synthesis

General experimental procedures • All chemicals (Acros, Fluka, Merck, and Sigma-Aldrich) were used as received unless stated otherwise. Dichloromethane was stored over activated 4 Å molecular sieves (beads, 8-12 mesh, Sigma-Aldrich). Before use traces of water present in the donor, diphenyl sulfoxide (Ph_2SO) and tri-*tert*-butylpyrimidine (TTBP) were removed by co-evaporation with dry toluene. The acceptor (triethylsilane-*d*) was stored in stock solutions (DCM, 0.5 M) over activated 4 Å molecular sieves. Trifluoromethanesulfonic anhydride (Tf_2O) was distilled over P_2O_5 and stored at −20 °C under a nitrogen atmosphere. Overnight temperature control was achieved by an FT902 Immersion Cooler (Julabo). Column chromatography was performed on silica gel 60 Å (0.04 – 0.063 mm, Screening Devices B.V.). Size exclusion chromatography was carried out on Sephadex™ (LH-20, GE Healthcare Life Sciences) by isocratic elution with DCM:MeOH (1:1, v:v). TLC-analysis was conducted on TLC Silica gel 60 (Kieselgel 60 F_{254}, Merck) with UV detection by (254 nm) and by spraying with 20% sulfuric acid in ethanol followed by charring at ± 150 °C or by spraying with a solution of $(NH_4)_6Mo_7O_{24}{\cdot}H_2O$ (25 g/l) and $(NH_4)_4Ce(SO_4)_4{\cdot}_2H_2O$ (10 g/l) in 10% sulfuric acid in water followed by charring at ± 260 °C. High-resolution mass spectra were recorded on a Thermo Finnigan LTQ Orbitrap mass spectrometer equipped with an electrospray ion source in positive mode (source voltage 3.5 kV, sheath gas flow 10, capillary temperature 275 °C) with resolution R=60.000 at m/z=400 (mass range = 150-4000). ^1H, ^2H and ^{13}C NMR spectra were recorded on a Bruker AV-400 NMR instrument (400, 61 and 101 MHz respectively), a Bruker AV-500 NMR instrument (500, 75 and 126 MHz respectively), or a Bruker AV-600 NMR instrument (600, 92 and 150 MHz respectively). For samples measured in $CDCl_3$ chemical shifts (δ) are given in ppm relative to tetramethylsilane as an internal standard or the residual signal of the deuterated solvent. Coupling constants (*J*) are given in Hz. To get better resolution of signals with small coupling constants or overlapping signals a gaussian window function (LB = ± −1 and GB = ± 0.5) was used on the ^1H NMR spectrum. All given ^{13}C APT spectra are proton decoupled. NMR peak assignment was made using COSY, HSQC. If necessary additional NOESY, HMBC and HMBC-GATED experiments were used to elucidate the structure. The anomeric product ratios were based on the integration of ^1H NMR. If the stereochemistry of the coupled product could not be confirmed a deprotection step was performed to verify the stereochemistry. IR spectra were recorded on a Shimadzu FTIR-8300 IR spectrometer with a resolution of 4 cm^{-1} and are reported in cm^{-1}. Specific rotations were measured on an MCP 100 Anton Paar polarimeter in $CHCl_3$ (10 mg/mL) at 589 nm unless stated otherwise.

General procedure V: synthesis of phenyl 2,3,4-tri-*O*-benzyl/methyl-1-thio-pentopyranoses • To a suspension of the corresponding pentose (10 mmol to 40 mmol) in pyridine (0.40 M), Ac_2O (12 eq.) was added dropwise at 0 °C. The mixture was allowed to warm to room temperature and stirred for 16 h. The reaction was quenched with sat. aq. $NaHCO_3$ and diluted with H_2O. The resulting product was extracted with DCM (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. The crude product was dissolved in DCM (0.15 M) and cooled to 0 °C. Hydrogen bromide (33 wt% in AcOH, 4.4 eq.) was added dropwise, and the reaction was allowed to warm to room temperature and stirred for an additional 16 h. Subsequently, the reaction mixture was concentrated under reduced pressure and co-evaporated with toluene (3x). To a solution of the crude product and thiophenol (1.05 eq.) in DMF (0.5 M), NaH (60% dispersion in mineral oil, 1.05 eq.) was added portion wise at 0 °C. After stirring for 16 h, the reaction was quenched by the addition of aqueous HCl (0.02 M) and diluted with H_2O. The resulting crude product was extracted with Et_2O (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated *in vacuo*. Column chromatography yielded an inseparable pyranose/furanose mixture. To a solution of the crude product in MeOH (0.2 M), NaOMe (0.2 eq.) was added portion wise. The reaction mixture was stirred for 1 h after which Amberlite IR120 H^+ was added until pH 6 was reached. The resulting suspension was filtered, concentrated under reduced pressure and co-evaporated with toluene (3x). The crude product was dissolved in DMF (0.25 M) and cooled to 0 °C. NaH (60% dispersion in mineral oil, 4 eq.) was added, and the resulting mixture was stirred for 10 min. Subsequently, benzyl bromide (4 eq.) or methyl iodide (4 eq.) was added, and the reaction mixture was allowed to warm up to room temperature and stirred for an additional 16 h. The reaction was quenched with MeOH and diluted with H_2O, after which the resulting mixture was extracted with Et_2O (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure.

General procedure VI: pre-activation Tf_2O/Ph_2SO based *d*-glycosylation • A solution of the donor (100 µmol), Ph_2SO (26 mg, 130 µmol, 1.3 eq.) and TTBP (62 mg, 250 µmol, 2.5 eq.) in DCM (2 mL, 0.05 M) was stirred over activated 3 Å molecular sieves (rods, size 1/16 in., Sigma-Aldrich) for 30 min under an atmosphere of N_2. The solution was cooled to –80 °C and Tf_2O (22 µl, 130 µmol, 1.3 eq.) was slowly added to the reaction mixture. The reaction mixture was allowed to warm to –60 °C in approximately 45 min, followed by cooling to –80 °C and the addition of the acceptor (200 µmol, 2 eq.) in DCM (0.4 mL, 0.5 M). The reaction was allowed to warm up to –60 °C and stirred for an additional 80 h at this temperature to ensure reaction completion. The reaction was quenched with sat. aq. $NaHCO_3$ at –60 °C and diluted with DCM (5 mL). The resulting solution was washed with H_2O and brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Purification by column chromatography yielded the corresponding *d*-coupled glycoside.

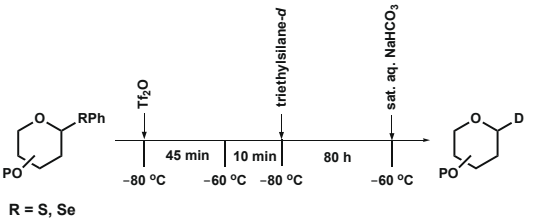


Figure S11. Schematic representation of the reaction procedure during pre-activation Ph_2SO/Tf_2O mediated glycosylation.

General procedure VII: debenzylation of *d*-coupled pyranoses • The *d*-coupled pyranose was dissolved in MeOH (0.02 M) under an atmosphere of N_2, and Pd/C (10 mol%) was added. Subsequently, H_2 was bubbled through the reaction mixture for approximately 15 min., and the reaction was stirred for an additional 32 h. The reaction was filtered over Celite® 545 (Sigma-Aldrich) and concentrated under reduced pressure. Purification by column chromatography yielded the corresponding deprotected *d*-coupled glycoside.

General procedure VIII: pre-activation Tf_2O/Ph_2SO based *d*-glycosylation in Et_2O or CH_3CN • A solution of the donor (100 µmol), Ph_2SO (26 mg, 130 µmol, 1.3 eq.) and TTBP (62 mg, 250 µmol, 2.5 eq.) in Et_2O (1.7 mL) or CH_3CN (1.7 mL) and DCM (0.7 mL) was stirred over activated 3 Å molecular sieves (rods, size 1/16 in., Sigma-Aldrich) for 30 min under an atmosphere of N_2. The solution was cooled to –80 °C and Tf_2O (22 µl, 130 µmol, 1.3 eq.) was slowly added to the reaction mixture. The reaction mixture was allowed to warm to –60 °C in approximately 45 min, followed by cooling to –80 °C and the addition of the acceptor (200 µmol, 2 eq.). The reaction was allowed to warm up to –60 °C and stirred for an additional 80 h at this temperature to ensure reaction completion. The reaction was quenched with sat. aq. $NaHCO_3$ at –60 °C and diluted with DCM (5 mL). The resulting solution was washed with H_2O and brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Purification by column chromatography yielded the corresponding *d*-coupled glycoside.

General procedure IX: TMSOTf activation based *d*-glycosylation • The imidate donor (100 µmol, 1 eq.) was co-evaporated twice with dry toluene and then dissolved in dry DCM (1 mL, 0.1 M). Activated 3 Å molecular sieves and the acceptor (200 µmol, 2 eq.) were added and the solution was stirred for 30 min at room temperature under an inert atmosphere.

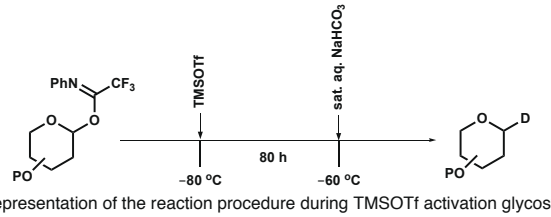
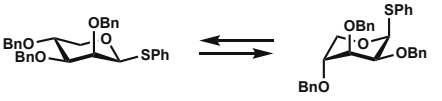


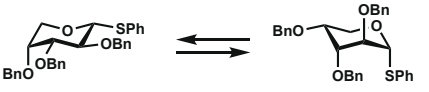
Figure S12. Schematic representation of the reaction procedure during TMSOTf activation glycosylation.

The reaction mixture was cooled to the –80 °C and a freshly prepared stock solution of TMSOTf in DCM (0.5 M) of was introduced via syringe (50 µL, 0.01 mmol, 0.1 eq.). The reaction was allowed to warm up to

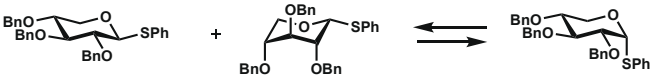
–60 °C and stirred for an additional 80 h, and was then quenched by the addition of sat. aq. $NaHCO_3$. The mixture was diluted with DCM and H_2O and twice extracted with DCM. The combined organic layers were dried with $MgSO_4$, filtered, and concentrated *in vacuo*. Purification by column chromatography yielded the corresponding *d*-coupled glycoside.



Phenyl 2,3,4-tri-*O*-benzyl-1-thio-D-lyxopyranoside (S6). The title compound was prepared according to general procedure V from D-lyxose. Column chromatography (100:0 → 95:5, pentane:EtOAc) yielded compound **S6** (643 mg, 1.22 mmol, 52% over 5 steps, average of 88% per step, colorless solid). TLC: R_f 0.21 (pentane:EtOAc, 9.5:0.5, v:v); $[\alpha]_D^{20}$ –87.0°; IR (thin film, cm^{-1}): 693, 748, 1049, 1217, 1367, 1438, 1743; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.54 – 7.15 (m, 20H, CH_{arom}), 5.30 (d, *J* = 4.0 Hz, 1H, H-1), 4.88 (d, *J* = 12.2 Hz, 1H, C*H*H Bn), 4.77 – 4.71 (m, 2H, CH_2 Bn), 4.68 (d, *J* = 12.2 Hz, 1H, CH*H* Bn), 4.55 (s, 2H, CH_2 Bn), 4.33 (dd, *J* = 12.3, 2.5 Hz, 1H, H-5), 4.18 (dd, *J* = 4.1, 2.5 Hz, 1H, H-2), 3.79 – 3.69 (m, 2H, H-3, H-4), 3.51 (dd, *J* = 12.2, 4.3 Hz, 1H, H-5); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 138.6, 138.1, 137.5 ($C_{q\text{-}arom}$), 130.6, 128.9, 128.5, 128.5, 128.4, 128.1, 127.9, 127.8, 127.7, 127.7, 126.7 (CH_{arom}), 87.9 (C-1), 77.2 (C-3), 75.7 (C-2), 75.2 (C-4), 73.4, 72.9, 72.0 (CH_2 Bn), 62.1 (C-5); ^{13}C-GATED NMR (101 MHz, $CDCl_3$): δ 87.9 ($J_{C1\text{-}H1}$= 160 Hz, 1,2-*cis*); HRMS: $[M+NH_4]^+$ calcd for $C_{32}H_{36}NO_4S$ 530.23596, found 530.23568.



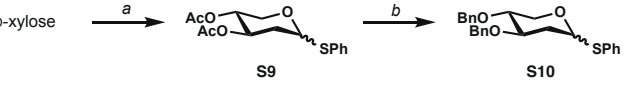
Phenyl 2,3,4-tri-*O*-benzyl-1-thio-D-arabinopyranoside (S7). The title compound was prepared according to general procedure V from D-arabinose. Column chromatography (100:0 → 95:5, pentane:EtOAc) yielded compound **S7** (2.21 g, 4.31 mmol, 50% over 5 steps, average of 87% per step, off-white solid). TLC: R_f 0.45 (pentane:EtOAc, 9.5:0.5, v:v); $[\alpha]_D^{20}$ –49.8°; IR (thin film, cm^{-1}): 731, 775, 1026, 1042, 1082, 1125, 1452, 2862; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.56 – 7.19 (m, 20H, CH_{arom}), 4.91 (d, *J* = 6.1 Hz, 1H, H-1), 4.70 (d, *J* = 11.0 Hz, 1H, C*H*H Bn), 4.68 – 4.61 (m, 4H, CH_2 Bn, CH_2 Bn), 4.59 (d, *J* = 12.3 Hz, 1H, CH*H* Bn), 4.26 (dd, *J* = 12.0, 5.8 Hz, 1H, H-5), 3.94 (t, *J* = 6.5 Hz, 1H, H-2), 3.82 (dt, *J* = 5.8, 2.8 Hz, 1H, H-4), 3.67 (dd, *J* = 6.9, 3.1 Hz, 1H, H-3), 3.44 (dd, *J* = 12.0, 2.6 Hz, 1H, H-5); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 138.3, 138.2, 138.1, 135.6 ($C_{q\text{-}arom}$), 131.3, 128.9, 128.5, 128.5, 128.4, 128.1, 127.9, 127.9, 127.9, 127.8, 127.1 (CH_{arom}), 87.3 (C-1), 78.6 (C-3), 77.4 (C-2), 74.3 (CH_2 Bn), 72.4 (C-4), 72.4, 71.2 (CH_2 Bn), 63.3 (C-5); ^{13}C-GATED NMR (101 MHz, $CDCl_3$): δ 83.3 ($J_{C1\text{-}H1}$= 158 Hz, 1,2-*trans*); HRMS: $[M+NH_4]^+$ calcd for $C_{32}H_{36}NO_4S$ 530.23596, found 530.23588.



Phenyl 2,3,4-tri-*O*-benzyl-1-thio-D-xylopyranoside (S8). The title compound was prepared according to general procedure V from D-xylose. Column chromatography (100:0 → 95:5, pentane:EtOAc) yielded compound **S8** (2.33 g, 4.40 mmol, 48% over 5 steps, average of 86% per step, yellow wax, 1,2-*cis*:1,2-*trans*; 23:77). TLC: R_f 0.42 (pentane:EtOAc, 9.5:0.5, v:v); IR (thin film, cm^{-1}): 694, 735, 1026, 1070, 1120, 1454, 2864, 3030; Data of the major stereoisomer (1,2-*trans* product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.54 – 7.25 (m, 20H, CH_{arom}), 4.89 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.85 (d, *J* = 10.1 Hz, 1H, C*H*H Bn), 4.83 (d, *J* = 10.9 Hz, 1H, CH*H* Bn), 4.75 (d, *J* = 10.0 Hz, 1H, CH*H* Bn), 4.71 (d, *J* = 11.6 Hz, 1H, C*H*H Bn), 4.67 (d, *J* = 9.5 Hz, 1H, H-1), 4.62 (d, *J* = 11.6 Hz, 1H, CH*H* Bn), 4.09 – 4.02 (m, 1H, H-5_{eq}), 3.67 – 3.60 (m, 2H, H-3, H-4), 3.44 (t, *J* = 8.7 Hz, 1H, H-2), 3.24 (dd, *J* = 11.5, 9.6 Hz, 1H, H-5_{ax}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 138.6, 138.2, 133.8, 132.0 ($C_{q\text{-}arom}$), 129.1, 128.6, 128.5, 128.5, 128.3, 128.1, 128.0, 128.0, 128.0, 127.9, 127.7 (CH_{arom}), 88.5 (C-1), 85.4 (C-3), 80.5 (C-2), 77.8 (C-4), 75.8, 75.6, 73.4 (CH_2 Bn), 67.6 (C-5); ^{13}C-GATED NMR (126 MHz, $CDCl_3$): δ 88.5 ($J_{C1\text{-}H1}$= 157 Hz, 1,2-*trans*); Data of the minor stereoisomer (1,2-*cis* product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.47 – 7.44 (m, 20H, CH_{arom}),

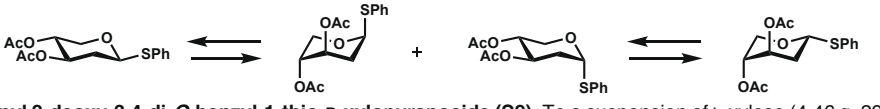
5.54 (d, *J* = 4.4 Hz, 1H, H-1), 4.93 (d, *J* = 10.8 Hz, 1H, C*H*H Bn), 4.76 (d, *J* = 10.6 Hz, 1H, C*H*H Bn), 4.63 (d, *J* = 11.7 Hz, 1H, CH*H* Bn), 3.82 – 3.78 (m, 2H, H-2, H-3), 3.71 – 3.66 (m, 2H, H-5, H-5). 3.61 – 3.53 (m, 1H, H-4); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 138.8, 138.4, 137.9, 134.6 ($C_{q\text{-}arom}$), 131.7, 129.1, 128.6, 128.5, 128.2, 128.2, 127.9, 127.8, 127.2 (CH_{arom}), 87.5 (C-1), 81.8 (C-3), 79.6 (C-2), 77.7 (C-4), 75.9, 73.7, 72.8 (CH_2 Bn), 61.2 (C-5); ^{13}C-GATED NMR (126 MHz, $CDCl_3$): δ 87.5 ($J_{C1\text{-}H1}$= 165 Hz, 1,2-*cis*); HRMS: $[M+NH_4]^+$ calcd for $C_{32}H_{36}NO_4S$ 530.23596, found 530.23589.

Preparation of donor S10

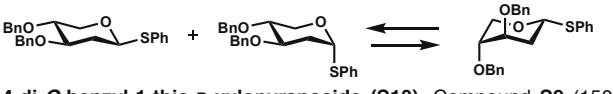


S9 **S10**

Scheme S1. Donor **S10** synthesis. *Reagents and conditions:* a) *i.* Ac_2O, pyridine; *ii.* HBr, AcOH, DCM; *iii.* Bu_3SnH, AIBN, toluene; *iv.* PhSH, $BF_3{\cdot}OEt_2$, DCM **S9**: 69%; b) *i.* NaOMe, MeOH, *ii.* BnBr, NaH, DMF, **S10**: 92%.

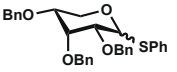


Phenyl 2-deoxy-3,4-di-*O*-benzyl-1-thio-D-xylopyranoside (S9). To a suspension of L-xylose (4.46 g, 29.7 mmol) in pyridine (72 mL), Ac_2O (34 mL, 356 mmol, 12 eq.) was added dropwise at 0 °C. After stirring for an additional 16 h at room temperature the mixture was concentrated *in vacuo* and co-evaporated three times with heptane. The crude product was dissolved in a mixture of DCM (55 mL) and Ac_2O (0.28 mL, 3.0 mmol, 0.1 eq.), HBr (33 wt% in AcOH, 23 mL, 127 mmol, 4.3 eq.) was added dropwise at 0 °C. The mixture was stirred for an additional 16 h at room temperature and subsequently concentrated under reduced pressure. The crude product was three times co-evaporated with toluene. The crude product was dissolved in toluene (1.2 L, 0.025 M) and AIBN (0.49 g, 2.97 mmol, 0.1 eq.) was added. The reaction was stirred at 80 °C for 30 min and Bu_3SnH (9.6 mL, 35.6 mmol, 1.2 eq.) was added dropwise over 16 h. The reaction mixture was concentrated and column chromatography (80:20 → 70:30, pentane:EtOAc) afforded the crude product. The crude product was dissolved in DCM (250 mL, 0.10 M) and cooled to −80 °C. Subsequently, thiophenol (3.4 mL, 32.7 mmol, 1.1 eq.) and $BF_3{\cdot}OEt_2$ (4.5 mL, 35.6 mmol, 1.2 eq.) were added dropwise to the solution and the reaction was allowed to warm up to room temperature in 4 h. The reaction mixture was quenched with sat. aq. $NaHCO_3$ and extracted with DCM (3x). The combined organic layers were dried with $MgSO_4$ and concentrated *in vacuo*. The residue was purified using column chromatography (pentane:EtOAc, 90:10 → 70:30) affording title compound **S9**. (6.36 g, 20.5 mmol, 69% over 4 steps, average of 91% per step, colorless oil, 1,3-*cis*:1,3-*trans*; 66:34). TLC: R_f 0.42 (pentane:EtOAc, 7:3, v:v); IR (thin film, cm^{-1}): 693, 743, 1026, 1049, 1220, 1368, 1736; Data of the major stereoisomer (1,3-*cis* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.65 – 7.18 (m, 5H, CH_{arom}), 5.10 (dd, *J* = 7.4, 4.0 Hz, 1H, H-1), 5.00 (td, *J* = 7.5, 4.5 Hz, 1H, H-3), 4.85 (td, *J* = 7.0, 4.0 Hz, 1H, H-4), 4.36 (dd, *J* = 12.2, 3.9 Hz, 1H, H-5), 3.49 (dd, *J* = 12.2, 6.7 Hz, 1H, H-5), 2.52 (dt, *J* = 13.9, 4.3 Hz, 1H, H-2), 2.11 (s, 3H, CH_3 Ac), 2.08 (s, 3H, CH_3 Ac), 1.95 (dt, *J* = 13.9, 7.6 Hz, 1H, H-2); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 170.1, 170.1 (C=O), 134.4 ($C_{q\text{-}arom}$), 131.8, 129.1, 127.7 (CH_{arom}), 82.8 (C-1), 69.0 (C-3), 68.5 (C-4), 63.6 (C-5), 34.1 (C-2), 21.3, 21.1 (CH_3 Ac); Data of the minor stereoisomer (1,3-*trans* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 5.33 (dd, *J* = 6.6, 3.9 Hz, 1H, H-1), 5.17 (td, *J* = 6.9, 4.2 Hz, 1H, H-3), 4.80 (td, *J* = 6.7, 4.1 Hz, 1H, H-4), 4.09 (dd, *J* = 12.2, 6.2 Hz, 1H, H-5), 3.89 (dd, *J* = 12.2, 3.7 Hz, 1H, H-5), 2.34 (ddd, *J* = 14.0, 6.6, 4.2 Hz, 1H, H-2), 2.09 (s, 3H, CH_3 Ac), 2.08 (s, 3H, CH_3 Ac); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 170.2, 169.8 (C=O), 134.2 ($C_{q\text{-}arom}$), 131.5, 127.7 (CH_{arom}), 82.2 (C-1), 68.3 (C-4), 68.2 (C-3), 63.1 (C-5), 33.9 (C-2), 21.2, 21.1 (CH_3 Ac); HRMS: $[M+Na]^+$ calcd for $C_{15}H_{18}NaO_5S$ 333.0767, found 333.0771.

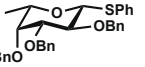


Phenyl 2-deoxy-3,4-di-*O*-benzyl-1-thio-D-xylopyranoside (S10). Compound **S9** (150 mg, 0.48 mmol) was dissolved in MeOH (4.8 mL, 0.1 M) and subsequently NaOMe (2.6 mg, 48 µmol 0.1 eq.) was added portionwise. The reaction mixture was stirred for 1 h after which Amberlite IR120 H^+ was added until pH 6 was reached. The resulting suspension was filtered, concentrated under reduced pressure and co-evaporated with toluene (3x). The crude product was dissolved in DMF (4.8 mL, 0.1 M) and cooled to 0 °C.

benzyl bromide (0.14 mL, 1.2 mL, 2.4 eq.) was added, and subsequently, NaH (60% dispersion in mineral oil, 46 mg, 1.2 mmol, 2.4 eq.) was added. The reaction mixture was allowed to warm up to room temperature and stirred for an additional 16 h. The reaction was quenched with MeOH and diluted with H_2O, after which the resulting mixture was extracted with Et_2O (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Column chromatography (95:5 → 85:15, pentane:EtOAc) gave the title compound **S10** (180 mg, 0.44 mmol, 92%, over 2 steps, average of 97% per step, colorless oil, 1,3-*cis*:1,3-*trans*; 62:38). TLC: R_f 0.31 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 694, 695, 735, 1026, 1077, 1089, 1206, 1440, 1454, 1480, 2846; Data of the major stereoisomer (1,3-*cis* product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.53 – 7.17 (m, 15H, CH_{arom}), 4.96 (dd, *J* = 8.9, 3.3 Hz, 1H, H-1), 4.72 (dd, *J* = 11.8, 3.3 Hz, 1H, C*H*H Bn), 4.65 – 4.55 (m, 3H, CH*H* Bn, C*H*H Bn, CH*H* Bn), 4.21 (dd, *J* = 11.9, 4.1 Hz, 1H, H-5_{eq}), 3.65 (ddd, *J* = 8.8, 7.1, 4.6 Hz, 1H, H-3), 3.51 (ddd, *J* = 14.2, 7.3, 4.0 Hz, 1H, H-4), 3.36 (dd, *J* = 11.9, 7.9 Hz, 1H, H-5_{ax}), 2.47 (ddd, *J* = 13.5, 4.6, 3.3 Hz, 1H, H-2_{eq}), 1.86 (dt, *J* = 13.5, 8.8 Hz, 1H, H-2_{ax}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.4, 138.4, 135.0 ($C_{q\text{-}arom}$), 131.3, 129.0, 128.6, 128.6, 127.9, 127.9, 127.8, 127.8, 127.8, 127.7, 127.3, 127.2 (CH_{arom}), 83.2 (C-1), 77.1 (C-3), 76.5 (C-4), 72.8, 71.9 (CH_2 Bn), 65.5 (C-5), 35.2 (C-2); Data of the minor stereoisomer (1,3-*trans* product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 5.43 (t, *J* = 4.7 Hz, 1H, H-1), 4.04 (dd, *J* = 11.9, 7.4 Hz, 1H, H-5), 3.83 (dd, *J* = 11.9, 4.0 Hz, 1H, H-3), 2.35 (ddd, *J* = 13.7, 5.2, 4.3 Hz, 1H, H-2), 2.04 (ddd, *J* = 13.2, 8.6, 4.4 Hz, 1H, H-2); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.5, 138.5, 134.9 ($C_{q\text{-}arom}$), 83.0 (C-1), 76.3 (C-3), 75.6 (C-4), 72.5, 72.0 (CH_2 Bn), 63.1 (C-5), 34.9 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{25}H_{26}O_3SNa$ 429.1495, found 429.1499.



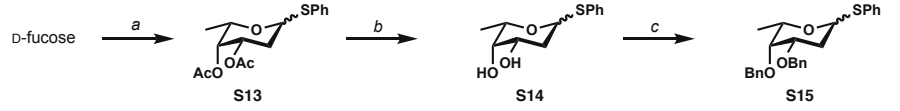
Phenyl 2,3,4-tri-*O*-benzyl-1-thio-D-ribopyranoside (S11). The title compound was prepared according to general procedure V from D-ribose. Column chromatography (95:5 → 90:10, pentane:EtOAc) yielded compound **S11** (1.02 g, 2.00 mmol, 25% over 5 steps, average of 76% per step yellow oil, 1,2-*cis*:1,2-*trans*; 32:68). TLC: R_f 0.39, 0.54 (pentane:EtOAc, 9.5:0.5, v:v); IR (thin film, cm^{-1}): 694, 735, 1026, 1060, 1087, 1454, 2873, 2926; Data of the major stereoisomer (1,2-*trans* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.55 – 7.19 (m, 20H, CH_{arom}), 5.22 (d, *J* = 9.0 Hz, 1H, H-1), 4.81 (s, 2H, CH_2 Bn), 4.61 – 4.54 (m, 4H, CH_2 Bn, CH_2 Bn), 4.13 (t, *J* = 2.5 Hz, 1H, H-3), 3.90 – 3.83 (m, 2H, H-5_{ax}, H-5_{eq}), 3.52 (ddd, *J* = 8.3, 5.9, 2.3 Hz, 1H, H-4), 3.33 (dd, *J* = 9.1, 2.5 Hz, 1H, H-2); ^{13}C NMR (101 MHz, $CDCl_3$): δ 138.9, 138.2, 137.9 ($C_{q\text{-}arom}$), 133.9, 131.8, 128.9, 128.6, 128.5, 128.3, 128.1, 128.0, 127.6 (CH_{arom}), 84.4 (C-1), 77.8 (C-2), 75.3 (C-4), 74.4 (C-3), 74.1, 72.4, 71.5 (CH_2 Bn), 64.6 (C-5); ^{13}C-GATED NMR (101 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 84.4 ($J_{C1\text{-}H1}$ = 161 Hz); Data of the minor stereoisomer (1,2-*cis* isomer product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.56 – 7.18 (m, 20H, CH_{arom}), 5.46 (d, *J* = 5.5 Hz, 1H, H-1), 5.03 (d, *J* = 12.4 Hz, 1H, C*H*H Bn), 4.89 (d, *J* = 12.5 Hz, 1H, CH*H* Bn), 4.71 (d, *J* = 11.9 Hz, 1H, C*H*H Bn), 4.61 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.51 (m, 1H, C*H*H Bn), 4.45 (d, *J* = 12.1 Hz, 1H, CH*H* Bn), 4.40 (t, *J* = 10.8 Hz, 1H, H-5_{ax}), 4.16 (d, *J* = 2.5 Hz, 1H, H-3), 3.70 (dd, *J* = 5.5, 2.2 Hz, 1H, H-2), 3.63 (dd, *J* = 10.9, 5.0 Hz, 1H, H-5_{eq}), 3.49 – 3.44 (m, 1H, H-4); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 139.1, 138.6 , 138.2, 137.9 ($C_{q\text{-}arom}$), 131.1, 128.9, 128.6, 128.2, 128.0, 127.9, 127.9, 127.8, 127.8, 127.6, 127.6, 127.3, 126.8 (CH_{arom}), 87.0 (C-1), 77.0 (C-2), 74.4 (C-4), 74.0 (C-3), 74.0, 71.2, 70.9 (CH_2 Bn), 58.2 (C-5); ^{13}C-GATED NMR (101 MHz, $CDCl_3$): δ 87.0 ($J_{C1\text{-}H1}$ = 162 Hz); HRMS: $[M+NH_4]^+$ calcd for $C_{32}H_{36}NO_4S$ 530.23596, found 530.23579.



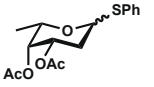
Phenyl 2,3,4-tri-*O*-benzyl-1-thio-β-L-fucopyranoside (S12). Compound **S12** was obtained from L-fucose, according to a literature procedure.[63] TLC: R_f 0.53 (pentane:Et_2O, 8:2, v:v); IR (thin film, cm^{-1}): 736, 868, 1043, 1053, 1059, 1441, 1479, 1584, 2855, 2897; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.65 – 7.16 (m, 20H, CH_{arom}), 5.01 (d, *J* = 11.6 Hz, 1H, C*H*H Bn), 4.79 (d, *J* = 10.2 Hz, 1H, CH*H* Bn), 4.75 – 4.64 (m, 4H, CH_2 Bn, CH_2 Bn), 4.60 (d, *J* = 9.6 Hz, 1H, H-1), 3.93 (t, *J* = 9.4 Hz, 1H, H-2), 3.64 (dd, *J* = 2.9, 0.9 Hz, 1H, H-4), 3.59 (dd, *J* = 9.2, 2.8 Hz, 1H, H-3), 3.53 (qd, *J* = 6.4, 1.0 Hz, 1H, H-5), 1.27 (d, *J* = 6.4 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.9, 138.5, 138.5 ($C_{q\text{-}arom}$), 134.5, 131.6, 128.9, 128.6, 128.5, 128.4, 128.3, 128.1, 127.8, 127.8, 127.7, 127.6, 127.1 (CH_{arom}), 87.7 (C-1), 84.7 (C-3), 77.3 (C-2),

76.8 (C-4), 75.7 (CH_2 Bn), 74.8 (C-5), 74.7, 73.0 (CH_2 Bn), 17.5 (CH_3); HRMS: $[M+H]^+$ calcd for $C_{33}H_{35}O_4S$ 527.22506, found 527.22479.

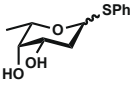
Preparation of donor S15



Scheme S2. Donor **S15** synthesis. *Reagents and conditions:* a) *i.* Ac_2O, pyridine; *ii.* HBr, AcOH, DCM; *iii.* Bu_3SnH, AIBN, toluene; *iv.* PhSH, $BF_3{\cdot}OEt_2$, DCM, **S13**: 61%; b) NaOMe, MeOH, **S14**: 97%; c) BnBr, NaH, DMF, **S15**: 92%.

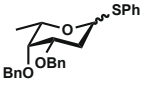


Phenyl 2-deoxy-3,4-di-*O*-acetyl-1-thio-L-fucopyranoside (S13). To a suspension of L-fucose (928 mg, 5.7 mmol) in pyridine (2.5 mL), Ac_2O (5 mL, 53 mmol, 12 eq.) was added dropwise at 0 °C. After stirring for an additional 16 h at room temperature the mixture was concentrated *in vacuo* and co-evaporated three times with heptane. The crude product was dissolved in a mixture of DCM (4 mL) and Ac_2O (0.25 mL, 2.6 mmol, 0.5 eq.), HBr (33 wt% in AcOH, 1.6 mL, 9.9 mmol, 1.8 eq.) was added dropwise at 0 °C. The mixture was stirred for an additional 4 h at room temperature and subsequently concentrated under reduced pressure. The crude product was dissolved in toluene (500 mL, 0.01 M) and AIBN (123 mg, 0.75 mmol, 0.1 eq.) was added. The reaction was stirred at 80 °C for 30 min and Bu_3SnH (3 mL, 11.3 mmol, 2 eq.) was added dropwise over 16 h. The reaction mixture was concentrated and column chromatography (90:10 → 80:20, pentane:EtOAc) afforded the crude product. The crude product was dissolved in DCM (40 mL, 0.15 M) and cooled to −80 °C. Subsequently, thiophenol (0.6 mL, 5.9 mmol, 1.05 eq.) and $BF_3{\cdot}OEt_2$ (0.79 mL, 6.2 mmol, 1.1 eq.) were added dropwise to the solution and the reaction was allowed to warm up to room temperature in 4 h. The reaction mixture was quenched with sat. aq. $NaHCO_3$ and extracted with DCM (3x). The combined organic layers were dried with $MgSO_4$ and concentrated *in vacuo*. The residue was purified using column chromatography (pentane:EtOAc, 90:10 → 70:30) affording title compound **S13**. (1.43 g, 3.4 mmol, 61% over 4 steps, average of 85% per step, colorless oil, 1,3-*cis*:1,3-*trans*; 20:80). TLC: R_f 0.45 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 884, 1024, 1060, 1224, 1366, 1440, 1480, 1742; Data of the major stereoisomer (1,3-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.55 – 7.22 (m, 5H, CH_{arom} SPh), 5.74 (d, *J* = 5.7 Hz, 1H, H-1), 5.28 (ddd, *J* = 12.6, 4.9, 3.0 Hz, 1H, H-3), 5.23 (d, *J* = 3.1 Hz, 1H, H-4), 4.56 (dt, *J* = 7.5, 6.0 Hz, 1H, H-5), 2.46 (td, *J* = 12.9, 5.9 Hz, 1H, H-2), 2.16 (s, 3H, CH_3 Ac), 2.10 – 2.02 (m, 1H, H-2), 2.01 (s, 3H, CH_3 Ac), 1.15 (d, *J* = 6.5 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 170.8, 170.1 (C=O Ac), 131.1, 129.1, 127.3 (C_{arom} SPh), 83.8 (C-1), 69.8 (C-3), 67.4 (C-4), 65.9 (C-5), 30.7 (C-2), 20.9 (CH_3 Ac), 16.6 (C-6); Data of the minor stereoisomer (1,3-*cis* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.55 – 7.22 (m, 5H, CH_{arom} SPh), 5.13 (d, *J* = 3.2 Hz, 1H, H-4), 5.01 (ddd, *J* = 10.1, 7.4, 3.1 Hz, 1H, H-3), 4.83 (dd, *J* = 8.3, 5.8 Hz, 1H, H-1), 3.73 (qd, *J* = 6.3, 0.9 Hz, 1H, H-5), 2.16 (s, 3H, CH_3 Ac), 2.12 – 2.02 (m, 2H, H-2, H-2), 2.00 (s, 3H, CH_3 Ac), 1.24 (d, *J* = 6.4 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 131.8, 129.0, 127.7 (CH_{arom} SPh), 82.5 (C-1), 73.4 (C-5), 70.0 (C-3), 68.7 (C-4), 31.5 (C-2), 21.1 (CH_3 Ac), 17.1 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{16}H_{20}NaO_5S$ 347.0929, found 347.0925.

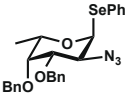


Phenyl 2-deoxy-1-thio-L-fucopyranoside (S14). Compound **S13** (243 mg, 0.75 mmol) was dissolved in MeOH (3 mL, 0.25 M), NaOMe (8 mg, 750 µmol, 0.1 eq.) was added portion wise to the stirred solution. After 4 h of stirring the reaction was quenched with Amberlite IR120 H^+. Filtration followed by column chromatography (50:50 → 20:80, pentane:EtOAc) afforded the title compound **S14** (0.78 g, 3.3 mmol, 97%, white solid, 1,3-*cis*:1,3-*trans*; 20:80). TLC: R_f 0.43 (pentane:EtOAc, 2:8, v:v); IR (neat, cm^{-1}): 733, 876, 968, 1092, 1165, 1373, 1585, 2882, 3348; Data of the major stereoisomer (1,3-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.56 – 7.17 (m, 5H, CH_{arom}), 5.65 (d, *J* = 5.7 Hz, 1H, H-1), 4.03 (ddd, *J* = 12.1, 5.3, 3.2 Hz, 1H, H-3), 3.79 – 3.53 (m, 2H, H-4, H-5), 2.84 – 2.29 (m, 2H, 3-OH, 4-OH), 2.29 – 2.04

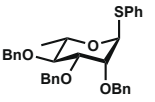
(m, 1H, H-2), 2.18 – 1.70 (m, 1H, H-2), 1.28 (d, *J* = 6.6 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 135.1 ($C_{q\text{-}arom}$), 131.6, 131.1, 129.1, 127.2 (CH_{arom}), 84.0 (C-1), 71.4 (C-4), 67.0 (C-5), 66.7 (C-3), 33.6 (C-2), 16.8 (CH_3). Data of the minor stereoisomer (1,3-*cis* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.56 – 7.17 (m, 5H, CH_{arom}), 4.72 (dd, *J* = 12.0, 2.2 Hz, 1H, H-1'), 4.43 (q, *J* = 6.8 Hz, 1H, H-5'), 3.79 – 3.53 (m, 2H, H-3', H-4'), 2.84 – 2.29 (m, 2H, 3-OH, 4-OH), 2.29 – 2.04 (m, 1H, H-2), 2.18 – 1.70 (m, 1H, H-2), 1.35 (d, *J* = 6.5 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 134.0 ($C_{q\text{-}arom}$), 131.6, 129.1, 129.0, 127.6 (CH_{arom}), 82.5 (C-1), 74.8 (C-4), 70.6 (C-5), 69.8 (C-3), 34.7 (C-2), 17.3 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{12}H_{16}NaO_3S$ 263.0719, found 263.0717.



Phenyl 2-deoxy-3,4-di-*O*-benzyl-1-thio-L-fucopyranoside (S15). Compound **S14** (120 mg, 0.5 mmol) was dissolved in DMF (2.5 mL, 0.25 M) and cooled to 0 °C. NaH (60% dispersion in mineral oil, 44 mg, 1.1 mmol, 2.2 eq.) was added portion wise and the resulting mixture was stirred for 15 min. Subsequently, benzyl bromide (131 µL, 1.1 mmol, 2.2 eq.) was added and the reaction mixture was allowed to warm up to room temperature and stirred for an additional 16 h. The reaction was quenched with MeOH and diluted with H_2O, after which the resulting mixture was extracted with Et_2O (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Column chromatography (95:5 → 85:15, pentane:Et_2O) gave the title compound **S15** (194 mg, 0.46 mmol, 92%, white solid, 1,3-*cis*:1,3-*trans*; 39:61). TLC: R_f 0.42 and 0.62 (pentane:Et_2O, 9:1, v:v); IR (thin film, cm^{-1}): 691, 733, 957, 1026, 1057, 1099, 1362, 2866; Data of the major stereoisomer (1,3-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.63 – 7.16 (m, 15H, CH_{arom}), 5.76 (d, *J* = 5.6 Hz, 1H, H-1), 4.98 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.71 (m, 1H, CH*H* Bn) 4.66 (d, *J* = 12.8 Hz, 1H, C*H*H Bn), 4.62 (d, *J* = 11.9 Hz, 1H, CH*H* Bn), 4.27 (q, *J* = 6.5 Hz, 1H, H-5), 3.91 (ddd, *J* = 12.3, 4.4, 2.5 Hz, 1H, H-3), 3.70 – 3.63 (m, 1H, H-4), 2.60 (td, *J* = 12.7, 5.8 Hz, 1H, H-2_{ax}), 2.16 (dd, *J* = 13.0, 4.5 Hz, 1H, H-2_{eq}), 1.19 (d, *J* = 6.5 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.9, 138.4, 135.7 ($C_{q\text{-}arom}$), 131.3, 130.6, 129.0, 128.8, 128.6, 128.4, 128.3, 127.8, 127.5 (CH_{arom}), 84.4 (C-1), 76.1 (C-3/C-4), 76.0 (C-3/C-4), 74.6 (CH_2 Bn), 70.6 (CH_2 Bn), 68.0 (C-5), 31.7 (C-2), 17.3 (CH_3); Data of the minor stereoisomer (1,3-*cis* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 4.98 (d, *J* = 11.8 Hz, 1H, C*H*H Bn), 4.74 – 4.68 (m, 1H, H-1), 4.69 (d, *J* = 11.8 Hz, 1H, C*H*H Bn), 4.63 (d, *J* = 12.1 Hz, 1H, CH*H* Bn), 4.57 (d, *J* = 12.1 Hz, 1H, CH*H* Bn), 3.59 (ddd, *J* = 11.5, 4.6, 2.5 Hz, 1H, H-3), 3.54 (dt, *J* = 2.5, 1.2 Hz, 1H, H-4), 3.46 (q, *J* = 5.7 Hz, 1H, H-5), 2.28 (q, *J* = 11.9 Hz, 1H, H-2_{ax}), 2.20 – 2.10 (m, 1H, H-2_{eq}), 1.26 (d, *J* = 6.4 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 139.0, 138.4 ($C_{q\text{-}arom}$), 134.7, 131.3, 128.8, 128.6, 128.3, 128.2, 127.7, 127.5, 127.4, 127.1, 127.0, 126.8 (CH_{arom}), 82.7 (C-1), 79.0 (C-3), 75.1 (C-5), 74.6 (C-4), 74.3 (CH_2 Bn), 70.3 (CH_2 Bn), 68.0 (CH_2 Bn), 32.1 (C-2), 17.8 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{26}H_{28}NaO_3S$ 443.1657, found 443.1651.

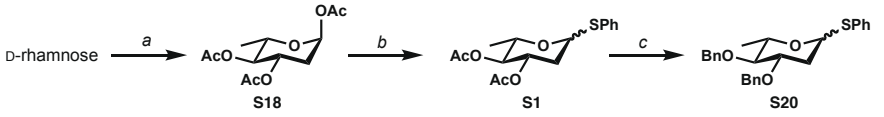


Phenyl 2-azido-2-deoxy-3,4-di-*O*-benzyl-1-seleno-β-L-fucopyranoside (S16). Compound **S16** was obtained from L-fucose, according to a literature procedure.[64] TLC: R_f 0.68 (pentane:Et_2O, 8:2, v:v); IR (thin film, cm^{-1}): 694, 737, 1064, 1105, 1454, 1744, 2106, 2855, 2922; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.63 – 7.18 (m, 15H, CH_{arom}), 5.93 (d, *J* = 5.3 Hz, 1H, H-1), 4.93 (d, *J* = 11.5 Hz, 1H, C*H*H Bn), 4.78 (d, *J* = 11.4 Hz, 1H, CH*H* Bn), 4.75 (d, *J* = 11.4 Hz, 1H, C*H*H Bn), 4.60 (d, *J* = 11.4 Hz, 1H, CH*H* Bn), 4.35 (dd, *J* = 9.9, 5.3 Hz, 1H, H-2), 4.22 (q, *J* = 6.5 Hz, 1H, H-5), 3.75 – 3.69 (m, 2H, H-3, H-4), 1.13 (d, *J* = 6.5 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.3, 137.6, 134.5 ($C_{q\text{-}arom}$), 129.1, 128.7, 128.4, 128.3, 128.2, 128.0, 127.9, 127.8 (CH_{arom}), 85.7 (C-1), 80.8 (C-3), 75.9 (C-4), 75.1, 72.7 (CH_2 Bn), 69.5 (C-5), 61.1 (C-2), 16.7 (CH_3); HRMS: $[M-N_2+NH_4]^+$ calcd for $C_{26}H_{28}NO_3Se$ 482.12289, found 482.12287.

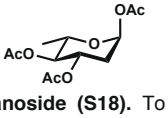


Phenyl 2,3,4-tri-*O*-benzyl-1-thio-β-L-rhamnopyranoside (S17). Compound **S17** was obtained from L-rhamnose, according to a literature procedure.[65] TLC: R_f 0.63 (pentane:Et_2O, 8:2, v:v); IR (thin film, cm^{-1}): 692, 732, 843, 908, 1024, 1070, 1082, 1205, 1452, 2868; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.48 – 7.10 (m, 20H, CH_{arom}), 5.49 (d, *J* = 1.6 Hz, 1H, H-1), 4.97 (d, *J* = 10.8 Hz, 1H, C*H*H Bn), 4.72 (d, *J* = 12.4 Hz, 1H, C*H*H Bn), 4.68 – 4.58 (m, 4H, CH_2 Bn, CH_2 Bn), 4.14 (dq, *J* = 9.3, 6.2 Hz, 1H, H-5), 3.99 (dd, *J* = 3.1, 1.7 Hz, 1H, H-2), 3.83 (dd, *J* = 9.3, 3.1 Hz, 1H, H-3), 3.68 (t, *J* = 9.3 Hz, 1H, H-4), 1.35 (d, *J* = 6.2 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.6, 138.3, 138.0, 134.8 ($C_{q\text{-}arom}$), 131.4, 129.1, 128.5, 128.5, 128.1, 128.1, 127.9, 127.9, 127.8, 127.4 (CH_{arom}), 85.9 (C-1), 80.6 (C-4), 80.1 (C-3), 76.6 (C-2), 75.6, 72.2, 72.2 (CH_2 Bn), 69.4 (C-5), 18.1 (CH_3); HRMS: $[M+H]^+$ calcd for $C_{33}H_{35}O_4S$ 527.22506, found 527.22483.

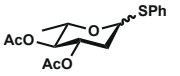
Preparation of donor S20



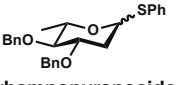
Scheme S3. Donor **S20** synthesis. *Reagents and conditions:* a) *i.* Ac_2O, pyr; *ii.* HBr, AcOH, DCM; *iii.* $CuSO_4{\cdot}5H_2O$, Ac_2O, NaOAc, AcOH, Zn; *iv.* Ac_2O, HBr, AcOH, **S18**: 60%; b) PhSH, $BF_3{\cdot}Et_2O$, DCM, **S19**: 97%; c) *i.* NaOMe, MeOH, *ii.* BnBr, NaH, DMF, **S20**: 95%.



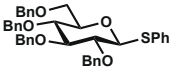
2-deoxy-1,3,4-tri-*O*-acetyl-α-L-rhamnopyranoside (S18). To suspension of L-rhamnose (4.5 g, 27.5 mmol) in pyridine (25 mL), Ac_2O (32 mL, 340 mmol, 12 eq.) at 0 °C. After stirring for an additional 16 h at room temperature the mixture was concentrated *in vacuo* and co-evaporated three times with heptane. The resulting colorless oil was used in the next step without further purification. The crude product was dissolved in DCM (18 mL), followed by the addition of Ac_2O (1.0 mL, 11 mmol, 0.4 eq.). To the solution HBr (33 wt% in AcOH, 8.5 mL, 55.0 mmol, 2.0 eq.) was added dropwise at 0 °C and stirred for an additional 4 h at room temperature The mixture was then concentrated under reduced pressure and the yellow oil was used as a crude product in the next step. Copper sulfate pentahydrate (0.88 g), Ac_2O (3.6 mL, 38 mmol, 1.4 eq.), sodium acetate (4.5 g, 55 mmol, 2 eq.), AcOH (3.2 mL) were suspended in acetonitrile (12 mL), and subsequently Zn (dust, 3.6 g, 55 mmol, 2 eq.) was added. After 45 min of stirring the rhamnosyl bromide was added in 60 mL acetonitrile via a dropping funnel over 40 min. The reaction was allowed to stir for an additional 2 h. After reaction completion the mixture was diluted with DCM and filtrated over Celite® 545 (Sigma-Aldrich) and transferred to a separatory funnel. The organic phase was washed with saturated sat. aq. $NaHCO_3$, dried with $MgSO_4$ and concentrated *in vacuo*. The crude rhamnal was dissolved in DCM (40 mL) and AcOH (15.8 mL, 276 mmol, 10 eq.), Ac_2O (22.2 mL, 233 mmol, 8.5 eq.) were added at 0 °C. After 15 min stirring, HBr (33 wt% in AcOH, 1.5 mL, 9.1 mmol, 0.3 eq.) was dropwise added at 0 °C and the reaction was stirred for an additional 5 h. After reaction completion the mixture was diluted with ice-cold water and extracted DCM (3x). The combined organic layers were washed with sat. aq. $NaHCO_3$, dried with $MgSO_4$ and concentrated *in vacuo*. Column chromatography (95:5 → 85:15, pentane:EtOAc) gave the title compound **S18** (4.5 g, 16.4 mmol, 60% over 4 steps, average of 88% per step, white solid). TLC: R_f 0.26 (pentane:EtOAc, 8:2, v:v); IR (neat, cm^{-1}): 922, 1037, 1134, 1157, 1369, 1732, 2994; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 6.19 (dd, *J* = 3.8, 1.4 Hz, 1H, H-1), 5.27 (ddd, *J* = 11.6, 9.5, 5.3 Hz, 1H, H-3), 4.80 (t, *J* = 9.7 Hz, 1H, H-4), 3.94 (dq, *J* = 9.8, 6.2 Hz, 1H, H-5), 2.26 (ddd, *J* = 13.5, 5.3, 1.5 Hz, 1H, H-2), 2.12 (s, 3H, CH_3 Ac), 2.07 (s, 3H, CH_3 Ac), 2.03 (s, 3H, CH_3 Ac), 1.92 (ddd, *J* = 13.5, 11.7, 3.7 Hz, 1H, H-2), 1.19 (d, *J* = 6.3 Hz, 3H, CH_3); ^{13}C NMR (126 MH, $CDCl_3$, HSQC): δ 170.4, 170.1, 169.3 (C=O, Ac), 90.9 (C-1), 74.2 (C-4), 68.5 (C-3), 68.3 (C-5), 34.3 (C-2), 21.2 (CH_3 Ac), 21.1 (CH_3 Ac), 20.9 (CH_3 Ac), 17.7 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{12}H_{18}NaO_7$ 297.0950, found 297.0951.



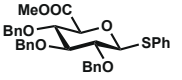
Phenyl 2-deoxy-3,4-di-*O*-acetyl-1-thio-L-rhamnopyranoside (S19). Compound **S18** (400 mg, 1.46 mmol) was dissolved in DCM (10 mL, 0.15M), and thiophenol (0.20 mL, 1.90 mmol, 1.3 eq.) was added, followed by the dropwise addition of $BF_3{\cdot}OEt_2$ (0.21 mL, 1.63 mmol, 1.1 eq.) at −80 °C. The reaction mixture was allowed to warm to room temperature in approximately 4 h. After 4 h, the reaction mixture quenched with sat. aq. $NaHCO_3$. The water layer was extracted with DCM (2x). The combined organic layer layers were washed with sat. aq. $NaHCO_3$ and dried with $MgSO_4$ and concentrated *in vacuo*. Column chromatography (95:5 → 85:15, pentane:EtOAc) gave the title compound **S19** (460 mg, 1.42 mmol, 97%, colorless oil, 1,3-*cis*:1,3-*trans*; 36:64). TLC: R_f 0.52 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 741, 910, 1049, 1219, 1366, 1740, 2982; Data of the major stereoisomer (1,3-*trans* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.56 – 7.20 (m, 5H, CH_{arom} SPh), 5.60 (d, *J* = 5.6 Hz, 1H, H-1), 5.26 (ddd, *J* = 11.8, 9.3, 5.2 Hz, 1H, H-3), 4.83 – 4.71 (m, 1H, H-4), 4.37 (dq, *J* = 9.6, 6.2 Hz, 1H, H-5), 2.45 (ddd, *J* = 13.4, 5.2, 1.2 Hz, 1H, H-2_{eq}), 2.20 (ddd, *J* = 13.4, 11.8, 5.9 Hz, 1H, H-2_{ax}), 2.08 (s, 3H, Ac CH_3), 2.03 (s, 3H, Ac CH_3), 1.19 (d, *J* = 6.2 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 170.35, 170.31 (C=O, Ac), 134.67 ($C_{q\text{-}arom}$), 133.02, 132.41, 131.34, 129.14, 129.07, 127.41 (CH_{arom}), 83.14 (C-1), 74.91 (C-4), 69.45 (C-3), 66.90 (C-5), 36.01 (CH_3 Ac), 21.15 (CH_3 Ac), 21.01 (CH_3 Ac), 17.57 (CH_3); Data of the minor stereoisomer (1,3-*cis* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 4.98 (ddd, *J* = 11.4, 9.5, 5.4 Hz, 1H, H-3), 3.52 (dq, *J* = 9.6, 6.2 Hz, 1H, H-4), 2.05 (s, 3H, Ac CH_3), 2.01 (s, 3H, Ac CH_3), 1.83 (dt, *J* = 12.7, 11.6 Hz, 1H, Ac CH_3), 1.26 (d, *J* = 6.2 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 170.50, 170.21 (C=O, Ac), 81.69 (C-1), 74.46 (C-5), 73.89 (C-4), 71.88 (C-3), 36.69 (CH_3 Ac), 21.10 (CH_3 Ac), 20.98 (CH_3 Ac), 18.05 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{16}H_{20}NaO_5S$ 347.0929, found 347.0928.



Phenyl 2-deoxy-3,4-di-*O*-benzyl-1-thio-L-rhamnopyranoside (S20). Compound **S19** (400 mg, 1.2 mmol) was dissolved in MeOH (6 mL, 0.2 M), and NaOMe (7 mg, 120 µmol, 0.1 eq.) was added. The reaction mixture was stirred for 4 h, and subsequently quenched with Amberlite IR120 H^+ and filtrated. The resulting filtrate was concentrated *in vacuo*. The crude product was dissolved in DMF (6 mL, 0.2 M) and cooled to 0 ^{0}C, and NaH (60% dispersion in mineral oil, 109 mg, 2.7 mmol, 2.2 eq.). The resulting suspension was stirred for 15 min, and benzyl bromide (323 µL, 2.7 mmol, 2.2 eq.) was dropwise added. The reaction mixture was allowed to warm up to room temperature and stirred for an additional 16 h. The reaction was quenched with MeOH and diluted with H_2O. The resulting reaction mixture was extracted with Et_2O (3x), and the combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Column chromatography (95:5 → 85:15, pentane:Et_2O) gave the title compound **S20** (495 mg, 1.18 mmol, 95%, white solid, 1,3-*cis*:1,3-*trans*; 35:65). TLC: R_f 0.46 and 0.59 (pentane:Et_2O, 9:1, v:v); IR (thin film, cm^{-1}): 694, 737, 995, 1072, 2866; Data of the major stereoisomer (1,3-*trans* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.54 – 7.14 (m, 15H, CH_{arom}), 5.58 (dd, *J* = 5.8, 1.3 Hz, 1H, H-1), 4.96 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.70 – 4.64 (m, 4H, CH*H* Bn, CH_2 Bn), 4.23 (dq, *J* = 9.4, 6.2 Hz, 1H, H-5), 3.94 (ddd, *J* = 11.5, 8.6, 4.8 Hz, 1H, H-3), 3.17 (t, *J* = 9.0 Hz, 1H, H-4), 2.47 (ddd, *J* = 13.2, 4.7, 1.3 Hz, 1H, H-2_{eq}), 2.09 (ddd, *J* = 13.4, 11.6, 5.7 Hz, 1H, H-2_{ax}), 1.29 (d, *J* = 6.2 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.6, 138.5 ($C_{q\text{-}arom}$), 131.3, 129.0, 128.6, 128.5, 128.1, 127.9, 127.2 (CH_{arom}), 84.5 (C-4), 83.9 (C-1), 77.8 (C-3), 75.4 (CH_2 Bn), 72.0 (CH_2 Bn), 68.5 (C-5), 36.7 (C-2), 18.2 (CH_3); Data of the minor stereoisomer (1,3-*cis* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 4.94 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.73 (dd, *J* = 11.9, 2.0 Hz, 1H, H-1), 4.61 (d, *J* = 11.6 Hz, 1H, CH*H* Bn), 3.65 (ddd, *J* = 11.1, 8.7, 5.2 Hz, 1H, H-3), 3.39 (dq, *J* = 9.3, 6.1 Hz, 1H, H-5), 3.15 (t, *J* = 9.0 Hz, 1H, H-4), 1.79 (dt, *J* = 12.8, 11.6 Hz, 1H, H-2_{ax}), 1.36 (d, *J* = 6.2 Hz, 1H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.5, 138.3 ($C_{q\text{-}arom}$), 134.2, 131.4, 129.0, 128.2, 127.9, 127.5 (CH_{arom}), 83.5 (C-4), 82.0 (C-1), 80.6 (C-3), 75.8 (C-5), 75.5 (CH_2 Bn), 71.8 (CH_2 Bn), 37.3 (C-2), 18.6 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{26}H_{28}NaO_3S$ 443.1657, found 443.1651.

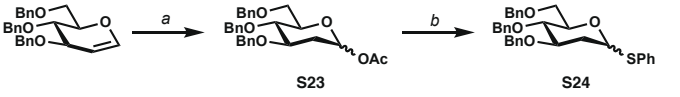


Phenyl 2,3,4,6-tetra-*O*-benzyl-1-thio-β-D-glucopyranoside (S21). Compound **S21** was obtained from D-glucose, according to a literature procedure.[66] TLC: R_f 0.73 (pentane:EtOAc, 9:1, v:v); $[\alpha]_D^{20}$ = 15.2° (*c* 1, DCM); IR (thin film, cm^{-1}): 714, 781, 1063, 1359, 1453, 2858, 2922; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.68 – 7.09 (m, 25H, CH_{arom}), 4.90 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.89 (d, *J* = 10.3 Hz, 1H, C*H*H Bn), 4.84 (d, *J* = 10.9 Hz, 1H, CH*H* Bn), 4.82 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.73 (d, *J* = 10.3 Hz, 1H CH*H* Bn), 4.67 (dd, *J* = 9.8, 0.9 Hz, 1H, H-1), 4.61 (d, *J* = 12.0 Hz, 1H C*H*H Bn), 4.59 (d, *J* = 10.8 Hz, 1H, CH*H* Bn), 4.54 (d, *J* = 12.0 Hz, 1H, CH*H* Bn), 3.79 (dd, *J* = 10.9, 1.9 Hz, 1H, H-6), 3.75 – 3.61 (m, 3H, H-3, H-4, H-6), 3.55 – 3.47 (m, 2H, H-2, H-5); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.5, 138.4, 138.2, 134.0 ($C_{q\text{-}arom}$), 132.1, 129.0, 128.6, 128.4, 128.1, 128.0, 127.9, 127.8, 127.8, 127.7, 127.6 (CH_{arom}), 87.6 (C-1), 86.9 (C-3), 81.0 (C-5), 79.2 (C-2), 78.0 (C-4), 76.0, 75.6, 75.2, 73.6 (CH_2 Bn), 69.2 (C-6); HRMS: $[M+Na]^+$ calcd for $C_{40}H_{40}NaO_5S$ 655.2494, found 655.2496.



Methyl (phenyl 2,3,4-tri-*O*-benzyl-1-thio-β-D-glucopyranosyl uronate) (S22). Compound **S22** was obtained from D-glucose, according to a literature procedure.[66] TLC: R_f 0.56 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 697, 738, 1026, 1073, 1209, 1439, 1453, 1750, 2856, 2924; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.71 – 7.08 (m, 20H, CH_{arom}), 4.88 (d, *J* = 10.3 Hz, 1H, C*H*H Bn), 4.88 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.84 (d, *J* = 10.9 Hz, 1H, CH*H* Bn), 4.78 (d, *J* = 10.8 Hz, 1H, C*H*H Bn), 4.73 (d, *J* = 10.2 Hz, 1H, CH*H* Bn), 4.68 (d, *J* = 9.8 Hz, 1H, H-1), 4.61 (d, *J* = 10.8 Hz, 1H, CH*H* Bn), 3.92 (d, *J* = 9.7 Hz, 1H, H-5), 3.84 (t, *J* = 9.4 Hz, 1H, H-4), 3.73 (s, 3H, CH_3 COOMe), 3.71 (t, *J* = 8.9 Hz, 1H, H-3), 3.52 (dd, *J* = 9.8, 8.7 Hz, 1H, H-2); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 168.8 (C=O), 138.2, 137.9, 137.8, 133.3 ($C_{q\text{-}arom}$), 132.3, 129.1, 128.6, 128.5, 128.5, 128.3, 128.1, 128.0, 128.0, 127.9 (CH_{arom}), 88.4 (C-1), 86.0 (C-3), 80.4 (C-2), 79.3 (C-4), 78.1 (C-5), 76.0, 75.6, 75.2 (CH_2 Bn), 52.6 (CH_3 COOMe); HRMS: $[M+Na]^+$ calcd for $C_{34}H_{34}NaO_6S$ 593.1968, found 593.1977.

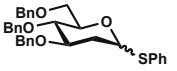
Preparation of donor S24



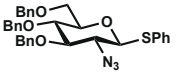
S23 S24

Scheme S4. Donor **S24** synthesis. *Reagents and conditions:* a) HBr·PPh_3, AcOH, **S23**: 83%; b) PhSH, *p*TsOH, DCM, **S24**: 91%.

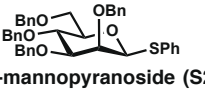
Phenyl 2-deoxy-3,4,6-tri-*O*-benzyl-1-thio-D-glucopyranoside (S23). Compound **S23** was obtained from 2-deoxy-tri-*O*-benzyl-D-glucal, according to a literature procedure as a mixture of stereoisomers (1,3-*cis*:1,3-*trans*; 10:90).[22] TLC: R_f 0.30 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 694, 734, 1026, 1078, 1362, 1454, 2863; Data of the major stereoisomer (1,3-*trans* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.47 – 7.06 (m, 15H, CH_{arom}), 6.25 (dd, *J* = 3.5, 1.5 Hz, 1H, H-1), 4.90 (d, *J* = 10.6 Hz, 1H, C*H*H Bn), 4.68 – 4.60 (m, 2H, C*H*H Bn, CH*H* Bn), 4.54 (d, *J* = 10.7 Hz, 1H, C*H*H Bn), 4.51 (d, *J* = 12.1 Hz, 1H, CH*H* Bn), 4.00 – 3.92 (m, 1H, CH*H* Bn), 3.96 (ddd, *J* = 11.4, 8.8, 4.9 Hz, 1H, H-3), 3.84 (dq, *J* = 9.9, 1.9 Hz, 1H, H-5), 3.78 (dd, *J* = 10.7, 3.5 Hz, 1H, H-6) 3.71 (dd, *J* = 9.8, 8.9 Hz, 1H, H-4), 3.66 (dd, *J* = 10.7, 1.9 Hz, 1H, H-6), 2.28 (ddd, *J* = 13.6, 5.0, 1.7 Hz, 1H, H-2_{eq}), 2.04 (s, 3H, CH_3 Ac), 1.84 (ddd, *J* = 13.6, 11.5, 3.5 Hz, 1H, H-2_{ax}); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 169.4 (C=O), 138.4, 138.3, 138.1 ($C_{q\text{-}arom}$), 128.5, 128.5, 128.1, 128.0, 127.8, 127.8, 127.8, 127.7 (CH_{arom}), 92.3 (C-1), 77.6 (C-4), 76.9 (C-3), 75.3 (CH_2 Bn), 73.6 (CH_2 Bn), 73.5 (C-5), 71.9 (CH_2 Bn), 68.5 (C-6), 34.3 (C-2), 21.2 (CH_3 Ac); Data of the minor stereoisomer (1,3-*cis* product): ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 5.67 (dd, *J* = 10.0, 2.2 Hz, 1H, H-1), 2.36 (ddd, *J* = 12.5, 4.9, 2.2 Hz, 1H, H-2_{eq}), 2.10 (s, 3H, CH_3 Ac). ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 169.4 (C=O), 92.9 (C-1), 75.1 (CH_2 Bn), 73.6 (CH_2 Bn), 71.8 (CH_2 Bn), 35.5 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{29}H_{32}NaO_6$ 499.2091, found 499.2096.



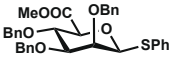
Phenyl 2-deoxy-3,4,6-tri-*O*-benzyl-1-thio-D-glucopyranoside (S24). Compound **S23** (0.7 g, 1.5 mmol) was dissolved in DCM (14 mL, 0.1 M), followed by the addition of thiophenol (0.3 mL, 3.0 mmol, 2 eq.) and *p*TsOH (0.56 g, 3.0 mmol, 2 eq.). After 16 h of stirring the reaction was quenched with sat. aq. $NaHCO_3$ and extracted with DCM (3x). The combined organic layers were washed with brine and dried over $MgSO_4$. Column chromatography (95:5 → 80:20, pentane:Et_2O) gave the title compound **S24** (702 mg, 1.33 mmol, 91%, colorless oil, 1,3-*cis*:1,3-*trans*; 40:60). TLC: R_f 0.60 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 694, 734, 1026, 1078, 1362, 1454, 2863; Data of the major stereoisomer (1,3-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.70 – 6.94 (m, 20H, CH_{arom}), 5.69 (dd, *J* = 5.6, 1.2 Hz, 1H, H-1), 4.90 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.74 – 4.51 (m, 4H, CH_2 Bn, CH_2 Bn, CH_2 Bn, CH_2 Bn), 4.46 (d, *J* = 12.0 Hz, 1H, CH*H* Bn), 4.30 (ddd, *J* = 9.8, 4.1, 2.0 Hz, 1H, H-5), 3.97 (ddd, *J* = 11.6, 8.7, 4.9 Hz, 1H, H-3), 3.90 – 3.76 (m, 1H, H-6), 3.73 (dd, *J* = 10.8, 4.6 Hz, 1H, H-5), 3.66 (ddd, *J* = 8.8, 5.0, 2.9 Hz, 1H, H-4), 2.49 – 2.41 (m, 1H, H-2_{eq}), 2.13 (ddd, *J* = 13.4, 11.7, 5.7 Hz, 1H, H-2_{ax}); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.5, 138.5, 138.2 ($C_{q\text{-}arom}$), 131.3, 129.0, 129.0, 128.6, 128.5, 128.5, 128.1, 128.0, 127.9, 127.8, 127.8 (CH_{arom}), 84.2 (C-1), 78.1 (C-4), 78.0 (C-3), 75.2, 73.5, 72.0 (CH_2 Bn), 71.8 (C-5), 68.9 (C-6), 36.4 (C-2). Data of the minor stereoisomer (1,3-*cis* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 4.75 (dd, *J* = 11.9, 1.9 Hz, 1H, H-1), 1.88 – 1.74 (m, 1H, H-2). ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 82.2 (C-1), 37.0 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{33}H_{34}NaO_4S$ 549.2070, found 549.2081.



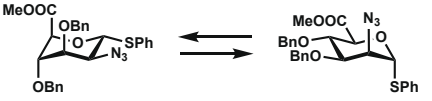
Phenyl 2-azido-2-deoxy-3,4,6-tetra-*O*-benzyl-1-thio-β-D-glucopyranoside (S25). Compound **S25** was obtained from D-glucosamine, according to a literature procedure.[67] TLC: R_f 0.61 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 697, 1101, 1105, 1146, 1276, 1453, 2109, 2856, 2919; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.60 (m, 2H, CH_{arom}), 7.35- 7.19 (m, 18H, CH_{arom}), 4.86 (d, *J* = 10.5 Hz, 1H, C*H*H Bn), 4.83 (d, *J* = 10.5 Hz, 1H, CH*H* Bn), 4.79 (d, *J* = 11.0 Hz, 1H, CH*H* Bn), 4.62 (d, *J* = 12.0 Hz, 1H, C*H*H Bn), 4.58 (d, *J* = 10.5 Hz, 1H, CH*H* Bn), 4.54 (d, *J* = 12.0 Hz, 1H, C*H*H Bn), 4.41 (d, *J* = 10.0 Hz, 1H, H-1), 3.80 – 3.71 (m, 2H, H-6), 3.61 (t, *J* = 9.5 Hz, 1H, H-4), 3.51 (t, *J* = 9.5 Hz, 1H, H-3), 3.47 (ddd, *J* = 2.0, 4.0, 9.5 Hz, 1H, H-5), 3.34 (t, *J* = 9.5 Hz, 1H, H-2); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.2, 137.8, 137.6 ($C_{q\text{-}arom}$), 133.6, 131.1, 129.0, 128.5, 128.4, 128.3, 128.2, 128.0, 127.9, 127.8, 127.6, 127.5 (CH_{arom}), 85.9 (C-1), 85.0 (C-3), 79.3 (C-5), 77.5 (C-4), 75.9, 75.0, 73.4 (CH_2 Bn), 68.7 (C-6), 65.0 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{33}H_{33}N_3NaO_4S$ 590.2084, found 590.2094.



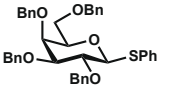
Phenyl 2,3,4,6-tetra-*O*-benzyl-1-thio-β-D-mannopyranoside (S26). Compound **S26** was obtained from D-mannose, according to a literature procedure.[19] TLC: R_f 0.81 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 694, 731, 1026, 1064, 1362, 1454, 2863, 3029; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.53 – 7.17 (m, 25H, CH_{arom}), 5.05 (d, *J* = 11.5 Hz, 1H, C*H*H Bn), 4.89 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.87 (d, *J* = 11.4 Hz, 1H, CH*H* Bn), 4.77 (d, *J* = 0.9 Hz, 1H, H-1), 4.73 (d, *J* = 11.8 Hz, 1H, CH*H* Bn), 4.69 (d, *J* = 11.8 Hz, 1H, C*H*H Bn), 4.60 (m, 2H, CH*H* Bn, C*H*H Bn), 4.55 (d, *J* = 11.8 Hz, 1H, CH*H* Bn), 4.15 (d, *J* = 2.2 Hz, 1H, H-2), 3.94 (t, *J* = 9.5 Hz, 1H, H-4), 3.84 (dd, *J* = 10.9, 1.8 Hz, 1H, H-6), 3.74 (dd, *J* = 10.9, 6.5 Hz, 1H, H-6), 3.63 (dd, *J* = 9.4, 2.9 Hz, 1H, H-3), 3.54 (ddd, *J* = 9.5, 6.5, 1.8 Hz, 1H, H-5); ^{13}C NMR ($CDCl_3$, 101 MHz, HSQC): δ 138.7, 138.4, 138.3, 138.2, 135.8 ($C_{q\text{-}arom}$), 130.7, 129.0, 128.6, 128.5, 128.4, 128.4, 128.3, 128.2, 127.9, 127.9, 127.8, 127.7, 127.5, 127.1 (CH_{arom}), 87.8 (C-1), 84.5 (C-3), 80.3 (C-5), 77.7 (C-2), 75.3 (CH_2 Bn), 75.2 (CH_2 Bn), 75.1 (C-4), 73.6 (CH_2 Bn), 72.7 (CH_2 Bn), 70.0 (C-6); ^{13}C-GATED NMR (101 MHz, $CDCl_3$): δ 87.8 ($J_{C1,H1}$ = 154 Hz, C-1 β); HRMS: $[M+NH_4]^+$ calcd for $C_{40}H_{44}NO_5S$ 650.29347, found 650.29381.



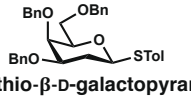
Methyl (phenyl 2,3,4-tri-*O*-benzyl-1-thio-β-D-mannopyranosyl uronate) (S27). Compound **S27** was obtained from D-mannose, according to a literature procedure.[66] TLC: R_f 0.40 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 695, 734, 1025, 1067, 1131, 1200, 1286, 1438, 1453, 1747, 2850; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.53 – 7.24 (m, 20H, CH_{arom}), 5.05 (d, *J* = 11.4 Hz, 1H, C*H*H Bn), 4.87 (d, *J* = 11.4 Hz, 1H, CH*H* Bn), 4.86 (d, *J* = 10.8 Hz, 1H, C*H*H Bn), 4.78 (d, *J* = 1.2 Hz, 1H, H-1), 4.74 – 4.67 (m, 3H, CH*H* Bn, C*H*H Bn, CH*H* Bn), 4.31 (t, *J* = 9.5 Hz, 1H, H-4), 4.14 (dd, *J* = 2.9, 1.2 Hz, 1H, H-2), 3.87 (d, *J* = 9.5 Hz, 1H, H-5), 3.72 (s, 3H, CH_3 COOMe), 3.62 (dd, *J* = 9.5, 2.9 Hz, 1H, H-3); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 168.4 (C=O), 138.2, 138.0, 135.2 ($C_{q\text{-}arom}$), 131.0, 129.1, 128.6, 128.5, 128.4, 128.3, 128.2, 128.0, 127.9, 127.8, 127.7, 127.5 (CH_{arom}), 89.0 (C-1), 83.5 (C-3), 78.9 (C-5), 77.4 (C-2), 75.7 (C-4), 75.4, 75.3, 72.9 (CH_2 Bn), 52.5 (C-5); HRMS: $[M+Na]^+$ calcd for $C_{34}H_{34}NaO_6S$ 593.1968, found 593.1981.



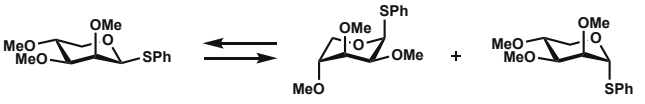
Methyl (phenyl 2-azido-2-deoxy-3,4-tri-*O*-benzyl-1-thio-α-D-mannopyranosyl uronate) (S28). Compound **S28** was obtained from D-mannosamine, according to a literature procedure. TLC: R_f 0.45 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 695, 736, 1025, 1119, 1206, 1439, 1453, 1750, 2102; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.65 – 7.26 (m, 15H, CH_{arom}), 5.61 (d, *J* = 7.6 Hz, 1H, H-1), 4.68 (d, *J* = 11.4 Hz, 1H, C*H*H Bn), 4.63 (d, *J* = 4.4 Hz, 1H, H-5), 4.59 (s, 2H, CH_2 Bn, CH_2 Bn), 4.21 (dd, *J* = 5.7, 4.4 Hz, 1H, H-4), 3.93 (dd, *J* = 5.7, 3.0 Hz, 1H, H-3), 3.72 (dd, *J* = 9.4, 3.5 Hz, 1H, H-2), 3.54 (s, 3H, CH_3 COOMe); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 169.5 (C=O), 137.5, 137.0 ($C_{q\text{-}arom}$), 132.6 (CH_{arom}), 132.2 ($C_{q\text{-}arom}$), 129.1, 128.6, 128.6, 128.3, 128.2, 128.2, 128.0, 127.9 (CH_{arom}), 82.3 (C-1), 77.2 (C-3), 74.9 (C-4), 73.2 (CH_2 Bn), 73.1 (C-5), 58.9 (C-2), 52.4 (CH_3 COOMe); HRMS: $[M+Na]^+$ calcd for $C_{27}H_{27}N_3NaO_5S$ 528.1564, found 528.1574.



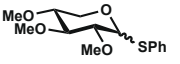
Phenyl 2,3,4,6-tetra-*O*-benzyl-1-thio-β-D-galactopyranoside (S29). Compound **S29** was obtained from D-galactose, according to a literature procedure.[68] TLC: R_f 0.75 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 714, 782, 1060, 1360, 1452, 2855, 2927; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC) δ 7.63 – 7.11 (m, 30H, CH_{arom}), 4.97 (d, *J* = 11.5 Hz, 1H, C*H*H Bn), 4.78 (d, *J* = 10.2 Hz, 1H, C*H*H Bn), 4.76 – 4.70 (m, 3H, CH*H* Bn, CH*H* Bn, C*H*H Bn), 4.64 (d, *J* = 9.7 Hz, 1H, H-1), 4.60 (d, *J* = 11.6 Hz, 1H, CH*H* Bn), 4.47 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.41 (d, *J* = 11.7 Hz, 1H, CH*H* Bn), 3.98 (dd, *J* = 2.8, 0.8 Hz, 1H, H-4), 3.93 (t, *J* = 9.4 Hz, 1H, H-2), 3.68 – 3.58 (m, 4H, H-3, H-5, H-6, H-6); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.9, 138.5, 138.4, 138.0, 134.3 ($C_{q\text{-}arom}$), 131.7, 128.9, 128.6, 128.5, 128.4, 128.1, 128.0, 127.9, 127.8, 127.7, 127.6, 127.2 (CH_{arom}), 87.9 (C-1), 84.3 (C-3), 76.9 (C-5), 76.8 (C-2), 75.8, 74.6 (CH_2 Bn), 73.7 (C-4), 72.9 (CH_2 Bn), 68.9 (C-6); HRMS: $[M+NH_4]^+$ calcd for $C_{40}H_{44}NO_5S$ 650.29347, found 650.29380.



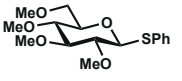
***p*-Tolyl 2-deoxy-3,4,6-tetra-*O*-benzyl-1-thio-β-D-galactopyranoside (S30).** Compound **S30** was obtained from D-galactose, according to a literature procedure.[70] TLC: R_f 0.65 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 656, 733, 808, 1027, 1061, 1093, 1360, 1454, 1493, 2862, 3029; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.45 – 6.99 (m, 20H, CH_{arom}), 4.93 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.68 (dd, *J* = 11.8, 2.2 Hz, 1H, H-1), 4.62 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.60 – 4.54 (m, 2H, CH*H* Bn, CH*H* Bn), 4.46 (d, *J* = 11.6 Hz, 1H, C*H*H Bn), 4.41 (d, *J* = 11.7 Hz, 1H, CH*H* Bn), 3.85 (s, 1H, H-4), 3.65 (m, 2H, H-6), 3.58 (ddd, *J* = 11.6, 4.5, 2.4 Hz, 1H, H-3), 3.53 (t, *J* = 6.1 Hz, 1H, H-5), 2.27 (q, *J* = 11.9 Hz, 1H, $H\text{-}2_{ax}$), 2.15 (dt, *J* = 12.9, 2.9 Hz, 1H, $H\text{-}2_{eq}$); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 139.1, 138.3, 138.2 ($C_{q\text{-}arom}$), 137.4 (CH_{arom}), 132.0 ($C_{q\text{-}arom}$), 130.6, 129.6, 128.6, 128.5, 128.3, 128.1, 128.0, 127.8, 127.8, 127.5, 127.5 (CH_{arom}), 83.4 (C-1), 78.5 (C-3), 78.1 (C-5), 74.2, 73.7 (CH_2 Bn), 71.9 (C-4), 70.3 (CH_2 Bn), 69.6, (C-6) 32.6 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{27}H_{29}NaO_4$ 440.1958, found 440.1960.



Phenyl 2,3,4-tri-*O*-methyl-1-thio-D-lyxopyranoside (S31). The title compound was prepared according to general procedure V from D-lyxose. Column chromatography (95:5 → 85:15, pentane:EtOAc) yielded compound **S31** (334 mg, 1.17 mmol, 27% over 5 steps, average of 77% per step, colorless oil, 1,2-*cis*:1,2-*trans*; 72:28). TLC: R_f 0.21 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 692, 743, 934, 1045, 1069, 1196, 1439, 1584, 2825, 2927; Data of the major stereoisomer (1,2-*cis* isomer product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.53 – 7.16 (m, 5H, CH_{arom} SPh), 5.29 (d, *J* = 4.1 Hz, 1H, H-1), 4.26 (dd, *J* = 9.8, 3.9 Hz, 1H, H-5), 3.88 (dd, *J* = 4.3, 2.5 Hz, 1H, H-2), 3.56 – 3.47 (m, 9H, H-3, H-4, H-5, CH_3 Me, CH_3 Me), 3.42 (d, *J* = 0.9 Hz, 3H, CH_3 Me); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 136.9 ($C_{q\text{-}arom}$ SPh), 130.2, 128.5, 126.4 (CH_{arom} SPh), 87.2 (C-1), 78.7 (C-3), 76.8 (C-2), 75.9 (C-4), 60.4 (C-5), 58.7, 57.9, 57.1 (CH_3 Me); ^{13}C-GATED NMR (126 MHz, $CDCl_3$): δ 87.2 ($J_{C1\text{-}H1}$= 158 Hz, 1,2-*cis*); Data of the minor stereoisomer (1,2-*trans* isomer product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC, HH-NOESY, HMBC-Gated): δ 7.53 – 7.16 (m, 5H, CH_{arom} SPh), 5.47 (d, *J* = 3.4 Hz, 1H, H-1), 3.92 – 3.80 (m, 2H, H-5_{ax}, H-5_{eq}), 3.76 (t, *J* = 3.3 Hz, 1H, H-2), 3.62 (td, *J* = 8.4, 4.8 Hz, 1H, H-4), 3.56 – 3.47 (m, 4H, H-3, CH_3 Me), 3.46 (s, 3H, CH_3 Me), 3.45 (s, 3H, CH_3 Me); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC, HMBC, HMBC-Gated): δ 134.1 ($C_{q\text{-}arom}$ SPh), 130.9, 128.7, 127.0 (CH_{arom} SPh), 84.8 (C-1), 79.4 (C-3), 78.1 (C-2), 75.8 (C-4), 61.7 (C-5), 58.4, 58.2, 57.8 (CH_3 Me); ^{13}C-GATED NMR (126 MHz, $CDCl_3$): δ 84.8 ($J_{C1\text{-}H1}$= 164 Hz, 1,2-*trans*); HRMS: $[M+Na]^+$ calcd for $C_{14}H_{20}NaO_4S$ 307.09745, found 307.09752.

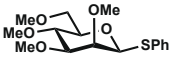


Phenyl 2,3,4-tri-*O*-methyl-1-thio-D-xylopyranoside (S32). The title compound was prepared according to general procedure V from D-xylose. Column chromatography (95:5 → 85:15, pentane:EtOAc) yielded compound **S32** (1.24 g, 4.35 mmol, 79%, colorless oil, 1,2-*cis*:1,2-*trans*; 18:82). TLC: R_f 0.29 (pentane:EtOAc, 8.5:1.5, v:v); IR (thin film, cm^{-1}): 692, 745, 1051, 1094, 1130, 1157, 1439, 1462, 2831, 2899, 2931; Data of the major stereoisomer (1,2-*trans* isomer product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC): δ 7.54 – 7.23 (m, 5H, CH_{arom} SPh), 4.59 (d, *J* = 8.9 Hz, 1H, H-1), 4.11 (dd, *J* = 11.3, 4.6 Hz, 1H, H-5_{eq}), 3.62 (s, 3H, CH_3 Me), 3.59 (s, 3H, CH_3 Me), 3.46 (s, 3H, CH_3 Me), 3.26 (ddd, *J* = 9.2, 8.2, 4.6 Hz, 1H, H-4), 3.23– 3.15 (m, 2H, H-3, H-5_{ax}), 3.07 (dd, *J* = 8.9, 7.9 Hz, 1H, H-2); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC, HMBC): δ 133.9 ($C_{q\text{-}arom}$), 131.9, 129.0, 127.5 (CH_{arom}), 87.8 (C-1), 86.5 (C-3), 82.0 (C-2), 79.1 (C-4), 66.4 (C-5), 60.7 (CH_3 Me, CH_3 Me), 58.7 (CH_3 Me); Data of the minor stereoisomer (1,2-*cis* isomer product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, HMBC): δ 5.65 (d, *J* = 5.3 Hz, 1H, H-1), 4.03 – 3.94 (m, 1H, H-5), 3.79 (dd, *J* = 11.5, 5.5 Hz, 1H, H-5), 3.64 (s, 3H, CH_3 Me), 3.52 (s, 3H, CH_3 Me), 3.50 (s, 3H, CH_3 Me), 3.35 (t, *J* = 9.0 Hz, 1H, H-3); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC, HMBC): δ 134.6 ($C_{q\text{-}arom}$), 131.6, 129.1, 127.3 (CH_{arom}), 87.0 (C-1), 82.9 (C-3), 61.1 (CH_3 Me), 60.7 (C-5), 59.1, 58.4 (CH_3 Me); HRMS: $[M+Na]^+$ calcd for $C_{14}H_{20}NaO_4S$ 307.09745, found 307.09757.

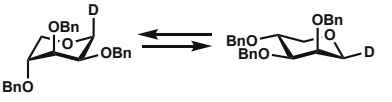


Phenyl 2,3,4,6-tetra-*O*-methyl-1-thio-β-D-glucopyranoside (S33). Phenyl 1-thio-β-D-glucose (1.36 g, 5.0 mmol)[19] was dissolved in DMF (25 mL, 0.25 M) and cooled to 0 °C. NaH (60% dispersion in mineral oil, 0.96 g, 24.0 mmol, 4.8 eq.) was added, and the resulting mixture was stirred for 10 min. Subsequently, methyl iodide (1.5 mL, 24.0 mmol, 4.8 eq.) was added, and the reaction mixture was allowed to warm up to room temperature and stirred for an additional 16 h. The reaction was quenched with MeOH and diluted with H_2O, after which the resulting mixture was extracted with Et_2O (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Column chromatography (75:15 → 80:20, pentane:EtOAc) yielded compound **S33** (1.05 g, 3.2 mmol, 64%, colorless solid). TLC: R_f 0.33 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 2932, 2833, 1097; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.64 – 7.21 (m, 5H, CH_{arom}), 4.52 (d, *J* = 9.8 Hz, 1H, H-1), 3.71 – 3.63 (m, 4H, CH_3, H-6), 3.63 (s, 3H, CH_3), 3.59 (dd, *J* = 10.8, 4.7 Hz, 1H, H-6), 3.56 (s, 3H, CH_3), 3.42 (s, 3H, CH_3), 3.32 (ddd, *J* = 9.4, 4.7, 2.0 Hz, 1H, H-5), 3.24 (t, *J* = 8.6 Hz, 1H, H-3), 3.19 (t, *J* = 9.3 Hz, 1H, H-4), 3.08 (dd, *J* = 9.8, 8.3 Hz, 1H, H-2); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 134.1 ($C_{q\text{-}arom}$), 131.8, 128.9, 127.4 (CH_{arom}),

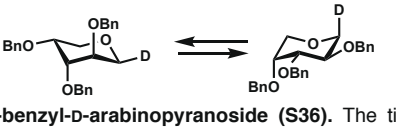
88.8 (C-4), 87.5 (C-1), 82.7 (C-2), 79.4 (C-3), 78.9 (C-5), 71.5 (C-6), 61.1, 61.0, 60.6, 59.5 (CH_3 Me); HRMS: $[M+Na]^+$ calcd for $C_{16}H_{24}NaO_5S$ 351.1237, found 351.1239.



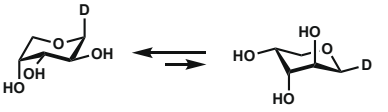
Phenyl 2,3,4,6-tetra-*O*-methyl-1-thio-β-D-mannopyranoside (S34). Phenyl 1-thio-β-D-mannose (0.5 g, 1.8 mmol)[19] was dissolved in DMF (9.2 mL, 0.2 M) and cooled to 0 °C. NaH (60% dispersion in mineral oil, 0.35 g, 8.8 mmol, 4.8 eq.) was added, and the resulting mixture was stirred for 10 min. Subsequently, methyl iodide (0.55 mL, 8.8 mmol, 4.8 eq.) was added, and the reaction mixture was allowed to warm up to room temperature and stirred for an additional 16 h. The reaction was quenched with MeOH and diluted with H_2O, after which the resulting mixture was extracted with Et_2O (3x). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered and concentrated under reduced pressure. Column chromatography (75:15 → 80:20, pentane:EtOAc) yielded compound **S34** (0.5 g, 1.5 mmol, 83%, colorless solid). TLC: R_f 0.30 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 2982, 2907, 1069, 737; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.74 – 7.04 (m, 5H, CH_{arom} SPh), 4.71 (d, *J* = 1.0 Hz, 1H, H-1), 3.89 (dd, *J* = 3.2, 1.0 Hz, 1H, H-2), 3.74 – 3.58 (m, 5H, CH_3, H-6), 3.53 (s, 6H, CH_3, CH_3), 3.45 (t, *J* = 9.5 Hz, 1H, H-4), 3.39 (s, 3H, CH_3), 3.31 (ddd, *J* = 9.7, 5.9, 1.9 Hz, 1H, H-5), 3.24 (dd, *J* = 9.3, 3.1 Hz, 1H, H-3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 135.5 ($C_{q\text{-}arom}$), 130.7, 128.9, 127.1 (CH_{arom}), 87.5 (C-1), 86.1 (C-3), 79.7 (C-5), 79.1 (C-2), 76.4 (C-4), 71.9 (C-6), 62.1, 60.9, 59.4, 58.1 (CH_3 Me); HRMS: $[M+Na]^+$ calcd for $C_{16}H_{24}NaO_5S$ 351.1237, found 351.1240.



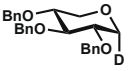
1-Deutero-1-deoxy-2,3,4-tri-*O*-benzyl-D-lyxopyranoside (S35). The title compound was prepared according to general procedure VI yielding compound **S35** (33 mg, 81 µmol, 81%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.57 (pentane:EtOAc, 9:1, v:v); $[\alpha]_D^{20}$ –30.2° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 731, 1026, 1096, 1350, 1452, 2875, 2916; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.38 – 7.26 (m, 15H, CH_{arom}), 4.71 (d, *J* = 12.1 Hz, 1H, C*H*H Bn), 4.65 – 4.58 (m, 5H, CH*H* Bn, CH_2 Bn, CH_2 Bn), 3.88 (dd, *J* = 11.8, 3.5 Hz, 1H, H-5), 3.82 (t, *J* = 3.0 Hz, 1H, H-2), 3.78 (td, *J* = 6.4, 3.5 Hz, 1H, H-4), 3.68 (dd, *J* = 6.7, 3.0 Hz, 1H, H-3), 3.47 (d, *J* = 2.8 Hz, 1H, H-1), 3.41 (dd, *J* = 11.7, 6.1 Hz, 1H, H-5); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.7, 138.4, 138.4 ($C_{q\text{-}arom}$), 128.5, 128.5, 128.5, 127.9, 127.9, 127.8, 127.8, 127.7 (CH_{arom}), 77.9 (C-3), 75.2 (C-4), 73.2 (C-2), 72.6, 71.6 (CH_2 Bn), 67.3 (C-5), 66.2 (t, *J* = 23.0 Hz, C-1); ^2H NMR (77 MHz, $CHCl_3$) δ 3.86 (D-1); HRMS: $[M+NH_4]^+$ calcd for $C_{26}H_{31}DNO_4$ 423.23941, found 423.23876.



1-Deutero-1-deoxy-2,3,4-tri-*O*-benzyl-D-arabinopyranoside (S36). The title compound was prepared according to general procedure VI yielding compound **S36** (35 mg, 86 µmol, 86%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.52 (pentane:EtOAc, 9:1, v:v); ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.38 – 7.26 (m, 15H, CH_{arom}), 4.71 (d, *J* = 12.2 Hz, 1H, C*H*H Bn), 4.68 – 4.57 (m, 5H, CH*H* Bn, CH_2 Bn, CH_2 Bn), 3.89 – 3.79 (m, 3H, H-1, H-2, H-5), 3.76 (dd, *J* = 6.6, 3.4 Hz, 1H, H-3), 3.68 (dd, *J* = 6.6, 2.4 Hz, 1H, H-4), 3.51 (t, *J* = 7.9 Hz, 1H, H-5); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.7, 138.4 ($C_{q\text{-}arom}$), 128.5, 128.5, 128.5, 127.9, 127.8, 127.8, 127.8, 127.7 (CH_{arom}), 77.7 (C-4), 75.1 (C-3), 73.3 (C-2), 72.6, 72.5, 71.5 (CH_2 Bn), 66.8 (t, *J* = 23.4 Hz, C-1), 66.4 (C-5); ^2H NMR (77 MHz, $CHCl_3$): δ 3.44 (D-1); HRMS: $[M+NH_4]^+$ calcd for $C_{26}H_{31}DNO_4$ 423.23941, found 423.23876.

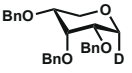


1-Deutero-1-deoxy-D-arabinopyranoside (S37). The title compound was prepared according to general procedure VII yielding compound **S37** (12 mg, 89 µmol, 89%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.53 (DCM:MeOH, 8:2, v:v); $[\alpha]_D^{20}$ –6.1° (*c* 0.25, MeOH); IR (thin film, cm^{-1}): 1014, 1410, 1449, 1647, 2951, 3294; ^{1}H NMR (400 MHz, Methanol-d_4, HH-COSY, HSQC, NOESY): δ 3.87 (dt, *J* = 5.8, 2.9 Hz, 1H, H-4), 3.79 (d, *J* = 3.8 Hz, 1H, H-1), 3.74 (dd, *J* = 7.4, 4.1 Hz, 1H, H-2), 3.72 (dd, *J* = 11.7, 5.2 Hz, 1H, H-5), 3.56 (dd, *J* = 7.4, 3.4 Hz, 1H, H-3), 3.50 (dd, *J* = 11.7, 2.6 Hz, 1H, H-5); ^{13}C NMR (101 MHz, MeOD, HSQC): δ 74.2 (C-3), 70.4 (C-5), 70.0 (t, *J* = 21.9 Hz, C-1), 69.3 (C-2), 69.0 (C-4); ^{2}H NMR (77 MHz, MeOH): δ 3.15 (D-1); HRMS: $[M+H]^+$ calcd for $C_5H_{10}DO_4$ 136.07201, found 136.07146.

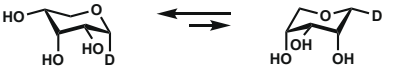


1-Deutero-1-deoxy-2,3,4-tri-*O*-benzyl-D-xylopyranoside (S38). The title compound was prepared according to general procedure VI yielding compound **S38** (35 mg, 86 µmol, 86%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.44 (pentane:EtOAc, 9:1, v:v); $[\alpha]_D^{20}$ –121.8° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 733, 1026, 1070, 1454, 1497, 2851, 2916; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.45 – 7.18 (m, 15H, CH_{arom}), 4.89 (s, 2H, CH_2 Bn), 4.73 (d, *J* = 11.6 Hz, 2H, CH_2 Bn), 4.63 (d, *J* = 11.6 Hz, 2H, CH_2 Bn), 3.96 – 3.90 (m, 2H, H-1, H-5_{eq}), 3.60 – 3.47 (m, 3H, H-2, H-3, H-4), 3.14 (dd, *J* = 11.1, 9.9 Hz, 1H, H-5_{ax}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.9, 138.4 ($C_{q\text{-}arom}$), 128.6, 128.5, 128.1, 127.9, 127.7 (CH_{arom}), 85.3 (C-3), 78.1, 78.1 (C-2/C-4), 75.6, 73.5, 73.5 (CH_2 Bn), 68.9 (C-5), 68.7, (t, *J* = 22.5 Hz, C-1); ^{2}H NMR (77 MHz, $CHCl_3$) δ 3.16 (D-1); HRMS: $[M+NH_4]^+$ calcd for $C_{26}H_{31}DNO_4$ 423.23941, found 423.23871.

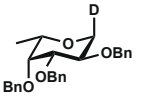
1-Deutero-1,2-di-deoxy-3,4-di-*O*-benzyl-D-xylopyranoside (S39). The title compound was prepared according to general procedure VI yielding compound **S39** (22 mg, 74 µmol, 74%, colorless oil, 1,3-*cis*:1,3-*trans*; >98:2). TLC: R_f 0.63 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{25}$ –16.2° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 730, 1020, 1077, 1456, 1496, 2850, 2910; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.65 – 6.57 (m, 10H, CH_{arom}), 4.74 (d, *J* = 11.8 Hz, 1H, C*H*H Bn), 4.71 – 4.63 (m, 3H, CH*H* Bn, C*H*H Bn, CH*H* Bn), 3.95 (dd, *J* = 11.5, 4.3 Hz, 1H, H-5), 3.58 (ddd, *J* = 9.1, 7.3, 4.5 Hz, 1H, H-3), 3.47 (ddd, *J* = 8.1, 7.3, 4.3 Hz, 1H, H-4), 3.39 (dd, *J* = 9.9, 2.8 Hz, 1H, H-1), 3.29 (dd, *J* = 11.5, 8.2 Hz, 1H, H-5), 2.06 (ddd, *J* = 13.4, 4.5, 2.9 Hz, 1H, H-2_{eq}), 1.64 (ddd, *J* = 13.4, 9.9, 9.2 Hz, 1H, H-2_{ax}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.8, 138.6 ($C_{q\text{-}arom}$), 128.5, 128.5, 127.9, 127.8, 127.7, 127.7 (CH_{arom}), 78.0 (C-3), 77.3 (C-4), 72.8, 71.7 (CH_2 Bn), 68.2 (C-5), 65.24 (t, *J* = 22.3 Hz, C-1), 30.3 (C-2); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.89 (D-1); HRMS: $[M+Na]^+$ calcd for $C_{19}H_{21}NaDO_3$ 322.1524, found 322.1526.



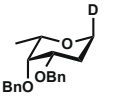
1-Deutero-1-deoxy-2,3,4-tri-*O*-benzyl-D-ribopyranoside (S40). The title compound was prepared according to general procedure VI yielding compound **S40** (28 mg, 69 µmol, 69%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.62 (pentane:EtOAc, 9:1, v:v); ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.56 – 7.17 (m, 15H, CH_{arom}), 4.88 (s, 2H, CH_2 Bn), 4.56 (d, *J* = 12.1 Hz, 2H, CH_2 Bn), 4.52 (d, *J* = 12.1 Hz, 2H, CH_2 Bn), 4.21 (t, *J* = 2.1 Hz, 1H, H-3), 3.74 – 3.68 (m, 3H, H-1, H-5, H-5), 3.48 – 3.43 (m, 3H, H-2, H-4); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 139.4, 138.3 ($C_{q\text{-}arom}$), 128.6, 128.3, 127.9, 127.8, 127.6, 127.4 (CH_{arom}), 75.8, 75.7 (C-2/C-4), 74.0 (C-3), 73.8, 71.2, 71.2 (CH_2 Bn), 64.5 (C-5), 64.2 (t, *J* = 22.7 Hz, C-1); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.71 (D-1); HRMS: $[M+NH_4]^+$ calcd for $C_{26}H_{31}DNO_4$ 423.23941, found 423.23877.



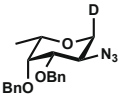
1-Deutero-1-deoxy-D-ribopyranoside (S41). The title compound was prepared according to general procedure VII yielding compound **S41** (12 mg, 89 µmol, 89%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.50 (DCM:MeOH, 8:2, v:v); $[\alpha]_D^{20}$ 10.5° (*c* 1, MeOH); IR (thin film, cm^{-1}): 1013, 1043, 1105, 1412, 1448, 1645, 2920, 3368; ^{1}H NMR (500 MHz, Methanol-d_4, HH-COSY, HSQC, NOESY): δ 3.86 (t, *J* = 2.9 Hz, 1H, H-3), 3.70 – 3.65 (m, 2H, H-2, H-4), 3.62 (dd, *J* = 11.0, 7.3 Hz, 1H, H-5), 3.54 – 3.48 (m, 2H, H-1, H-5); ^{13}C NMR (126 MHz, MeOD, HSQC): δ 68.9 (C-3), 67.9 (C-2), 67.9 (C-4), 67.8 (C-5), 66.6 (t, *J* = 21.5 Hz, C-1); ^{2}H NMR (77 MHz, MeOH): δ 3.57 (D-1); HRMS: $[M+H]^+$ calcd for $C_5H_{10}DO_4$ 136.07201, found 136.07141.



1-Deutero-1-deoxy-2,3,4-tri-*O*-benzyl-α-L-fucopyranoside (S42). The title compound was prepared according to general procedure VI yielding compound **S42** (31 mg, 74 µmol, 74%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). The title compound was also prepared according to general procedure VIII yielding compound **S42** (40 mg, 95 µmol, 95%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2) in Et_2O or yielding compound **S42** (23 mg, 55 µmol, 55%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2) in MeCN. The title compound was also prepared according to general procedure IX yielding compound **S42** (38 mg, 91 µmol, 91%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.54 (pentane:EtOAc, 9:1, v:v); $[\alpha]_D^{20}$ –35.0° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 694, 733, 1026, 1070, 1088, 1360, 1454, 1497, 2851, 2916; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.42 – 7.24 (m, 15H, CH_{arom}), 4.99 (d, *J* = 11.6 Hz, 1H, C*H*H Bn), 4.86 – 4.75 (m, 3H, CH*H* Bn, CH_2 Bn), 4.71 – 4.63 (m, 2H, CH_2 Bn), 4.06 – 4.00 (m, 2H, H-1, H-2), 3.64 (dd, *J* = 2.9, 1.1 Hz, 1H, H-4), 3.54 (dd, *J* = 8.7, 2.9 Hz, 1H, H-3), 3.40 (qd, *J* = 6.4, 1.1 Hz, 1H, H-5), 1.14 (d, *J* = 6.4 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.8, 138.6 ($C_{q\text{-}arom}$), 128.6, 128.5, 128.5, 128.3, 127.9, 127.8, 127.7, 127.7, 127.6 (CH_{arom}), 84.2 (C-3), 77.1 (C-4), 75.2 (C-5), 75.1 (CH_2 Bn), 74.9 (C-2), 73.6, 72.9 (CH_2 Bn), 66.8 (t, *J* = 23.5 Hz, C-1), 17.3 (CH_3); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.17 (D-1); HRMS: $[M+NH_4]^+$ calcd for $C_{27}H_{33}DNO_4$ 437.25506, found 437.25445.

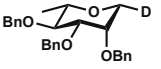


1-Deutero-1,2-di-deoxy-3,4-di-*O*-benzyl-α-L-fucopyranoside (S43). The title compound was prepared according to general procedure VI yielding compound **S43** (26 mg, 83 µmol, 83%, colorless oil, 1,3-*cis*:1,3-*trans*; <2:98). TLC: R_f 0.21 (pentane:EtOAc, 9:1, v:v); IR (thin film, cm^{-1}): 696, 733, 1028, 1063, 1082, 1105, 1175, 1364, 1454, 2855, 2927, 2949; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.54 – 7.18 (m, 10H, CH_{arom}), 4.98 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.71 (d, *J* = 11.7 Hz, 1H, CH*H* Bn), 4.65 (d, *J* = 12.1 Hz, 1H, C*H*H Bn), 4.60 (d, *J* = 12.2 Hz, 1H, CH*H* Bn), 4.01 (dd, *J* = 5.0, 1.7 Hz, 1H, H-1), 3.58 (dt, *J* = 2.5, 1.2 Hz, 1H, H-4), 3.55 (ddd, *J* = 11.7, 4.5, 2.5 Hz, 1H, H-3), 3.34 (qd, *J* = 6.4, 1.1 Hz, 1H, H-5), 2.16 (td, *J* = 12.2, 4.9 Hz, 1H, H-2_{ax}), 1.76 (ddt, *J* = 12.6, 4.5, 1.6 Hz, 1H, H-2_{eq}), 1.17 (d, *J* = 6.4 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 139.0, 138.7 ($C_{q\text{-}arom}$), 128.6, 128.6, 128.3, 127.7, 127.6, 127.4 (CH_{arom}), 79.2 (C-3), 76.0 (C-4), 75.1 (C-5), 74.6 (CH_2 Bn), 70.1 (CH_2 Bn), 65.8 (t, *J* = 21.2 Hz, C-1), 26.9 (C-2), 18.0 (CH_3); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.40 (D-1); HRMS: $[M+NH_4]^+$ calcd for $C_{20}H_{27}DNO_3$ 331.21320, found 331.21289.

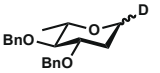


1-Deutero-2-azido-2-deoxy-3,4-di-*O*-benzyl-α-L-fucopyranoside (S44). The title compound was prepared according to general procedure VI yielding compound **S44** (23 mg, 65 µmol, 65%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.35 (pentane:EtOAc, 9:1, v:v); $[\alpha]_D^{20}$ –2.1° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 1123, 1265, 1724, 2106; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.47 – 7.27 (m, 10H, CH_{arom}), 4.95 (d, *J* = 11.5 Hz, 1H, C*H*H Bn), 4.76 (d, *J* = 11.6 Hz, 1H, C*H*H Bn), 4.71 (d, *J* = 11.6 Hz, 1H,

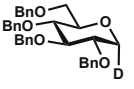
CH*H* Bn), 4.64 (d, *J* = 11.5 Hz, 1H, CH*H* Bn), 4.02 (dd, *J* = 9.6, 5.5 Hz, 1H, H-2), 3.97 (d, *J* = 5.5 Hz, 1H, H-1), 3.65 (d, *J* = 2.7 Hz, 1H, H-4), 3.43 (dd, *J* = 9.6, 2.7 Hz, 1H, H-3), 3.38 (q, *J* = 6.5 Hz, 1H, H-5), 1.17 (d, *J* = 6.3 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.3, 137.7 ($C_{q\text{-}arom}$), 128.7, 128.5, 128.4, 128.1, 128.0, 127.9 (CH_{arom}), 83.3 (C-3), 75.5 (C-2), 75.2 (C-5), 75.0, 72.2 (CH_2 Bn), 68.2 (t, *J* = 21.2 Hz, C-1), 58.3 (C-4), 17.5 (CH_3); ^2H NMR (77 MHz, $CHCl_3$): δ 3.08 (D-1); HRMS: $[M\text{-}N_2\text{+}H]^+$ calcd for $C_{20}H_{23}DNO_3$ 327.18135, found 327.18146.



1-Deutero-1-deoxy-2,3,4-tri-*O*-benzyl-β-L-rhamnopyranoside (S45). The title compound was prepared according to general procedure VI yielding compound **S45** (33 mg, 79 µmol, 79%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). The title compound was also prepared according to general procedure VIII yielding compound **S45** (36 mg, 86 µmol, 86%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2) in Et_2O or yielding compound **S45** (25 mg, 60 µmol, 60%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2) in MeCN. The title compound was also prepared according to general procedure IX yielding compound **S45** (39 mg, 93 µmol, 93%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.38 (pentane:EtOAc, 9:1, v:v); $[\alpha]_D^{20}$ 26.1° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 694, 733, 1026, 1092, 1113, 1354, 1452, 1497, 2860; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 7.46 – 7.26 (m, 15H, CH_{arom}), 4.99 (d, *J* = 10.8 Hz, 1H, C*H*H Bn), 4.81 (d, *J* = 12.7 Hz, 1H, CH*H* Bn), 4.72 – 4.61 (m, 3H, CH_2 Bn, C*H*H Bn), 4.57 (d, *J* = 11.9 Hz, 1H, CH*H* Bn), 3.75 (dd, *J* = 3.3, 1.0 Hz, 1H, H-2), 3.62 (t, *J* = 9.2 Hz, 1H, H-4), 3.53 (dd, *J* = 9.3, 3.2 Hz, 1H, H-3), 3.28 (dq, *J* = 9.0, 6.0 Hz, 1H, H-5), 3.24 (s, 1H, H-1), 1.36 (d, *J* = 6.2 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.7, 138.5, 138.4 ($C_{q\text{-}arom}$), 128.5, 128.2, 127.8, 127.7 (CH_{arom}), 82.8 (C-4), 80.8 (C-3), 76.5 (C-5), 75.7 (CH_2 Bn), 72.6 (C-2), 71.7, 71.3 (CH_2 Bn), 66.8 (t, *J* = 23.5 Hz, C-1), 18.4 (CH_3); ^2H NMR (77 MHz, $CHCl_3$): δ 4.03 (D-1); HRMS: $[M\text{+}NH_4]^+$ calcd for $C_{27}H_{33}DNO_4$ 437.25506, found 437.25446.

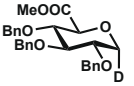


1-Deutero-1,2-di-deoxy-3,4-di-*O*-benzyl-L-rhamnopyranoside (S46). The title compound was prepared according to general procedure VI yielding compound **S46** (27 mg, 86 µmol, 86%, colorless oil, 1,3-*cis*:1,3-*trans*; 66:34). TLC: R_f 0.24 (pentane:Et_2O, 8:2, v:v); IR (thin film, cm^{-1}): 696, 735, 1089, 1107, 1360, 1454, 2855, 2924. Data of the major stereoisomer (1,3-*cis* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.38 – 7.21 (m, 10H, CH_{arom}), 4.96 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.70 (d, *J* = 11.7 Hz, 1H, CH*H* Bn), 4.66 (d, *J* = 10.9 Hz, 1H, C*H*H Bn), 4.63 (d, *J* = 11.7 Hz, 1H, CH*H* Bn), 3.59 (ddd, *J* = 11.4, 8.6, 5.1 Hz, 1H, H-3), 3.33 (dd, *J* = 12.8, 2.0 Hz, 0. 66H, H-1), 3.27 (dq, *J* = 9.2, 6.1 Hz, 1H, H-5), 3.10 (t, *J* = 8.9 Hz, 1H, H-4), 2.08 (ddd, *J* = 13.0, 5.1, 2.0 Hz, 1H, $H\text{-}2_{eq}$), 1.67 (td, *J* = 12.9, 11.3 Hz, 1H, $H\text{-}2_{ax}$), 1.30 (d, *J* = 6.1 Hz, 3H, CH_3); ^{13}C NMR (101 MHz, $CHCl_3$, HSQC): δ 138.7 ($C_{q\text{-}arom}$), 128.5, 128.5, 128.2, 127.8, 127.7 (CH_{arom}), 84.5 (C-4), 81.1 (H-3), 76.1 C-5), 75.5 (CH_2 Bn), 71.5 (CH_2 Bn), 65.2 (t, *J* = 22.4 Hz, C-1), 31.8 (C-2), 18.7 (CH_3); ^2H NMR (77 MHz, $CHCl_3$): δ 3.91 (D-1); Data of the minor stereoisomer (1,3-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): 3.88 (dd, *J* = 5.0, 1.7 Hz, 0.34 H, H-1'); ^2H NMR (77 MHz, $CHCl_3$): δ 3.36 (D-1'); HRMS: $[M\text{+}NH_4]^+$ calcd for $C_{20}H_{27}DNO_3$ 331.21320, found 331.21269.

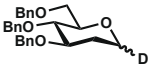


1-Deutero-1-deoxy-2,3,4,6-tetra-*O*-benzyl-α-D-glucopyranoside (S47). The title compound was prepared according to general procedure VI yielding compound **S47** (37 mg, 70 µmol, 70%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). The title compound was prepared according to general procedure IX yielding compound **S47** (48 mg, 91 µmol, 91%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.69 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{20}$ 5.3° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 698, 731, 1024, 1093, 1123, 1353, 1451, 1499, 2867; ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.61 – 6.96 (m, 20H, CH_{arom}), 4.97 (d, *J* = 11.0 Hz, 1H, C*H*H Bn), 4.84 (d, *J* = 11.0 Hz, 1H, CH*H* Bn), 4.83 (d, *J* = 10.7 Hz, 1H, C*H*H Bn), 4.71 (d, *J* = 11.6 Hz, 1H, C*H*H Bn), 4.63 (d, *J* = 11.6 Hz, 1H, CH*H* Bn), 4.59 (d, *J* = 12.2 Hz, 1H, C*H*H Bn), 4.50 (d, *J* = 12.2 Hz, 1H, CH*H* Bn), 4.48 (d, *J* = 10.7 Hz, 1H, CH*H* Bn), 4.01 (d, *J* = 4.5 Hz, 1H, H-1), 3.74 – 3.59 (m, 4H, H-2, H-6, H-6, H-5), 3.56 (ddd, *J* = 9.2, 5.7, 3.5 Hz, 1H, H-4), 3.37 (ddd, *J* = 9.5, 4.3, 2.1 Hz, 1H, H-3); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.8, 138.3, 138.2, 138.0 ($C_{q\text{-}arom}$), 128.6, 128.5, 128.5, 128.1, 128.1, 128.1, 128.0,

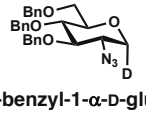
128.0, 127.9, 127.8, 127.7 (CH_{arom}), 86.5 (C-2/C-5), 79.3 (C-3), 78.5 (C-5/C-2), 77.9 (C-4), 75.7 (CH_2 Bn), 75.3 (CH_2 Bn), 73.7 (CH_2 Bn), 73.4 (CH_2 Bn), 69.1 (C-6), 67.9 (t, J = 21.5 Hz, C-1); HRMS: $[M+Na]^+$ calcd for $C_{34}H_{35}NaDO_5$ 548.2518, found 548.2521.



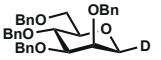
Methyl (2,3,4-tri-*O*-benzyl-1-deoxy-α-deuterio-D-glucopyranosyl uronate) (S48). The title compound was prepared according to general procedure VI yielding compound **S48** (20 mg, 43 µmol, 43%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.73 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{25}$ 54.5° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 695, 734, 1027, 1070, 1211, 1438, 1454, 1747, 2950; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.55 – 7.13 (m, 20H, CH_{arom}), 4.93 (d, J = 11.0 Hz, 1H, C*H*H Bn), 4.84 (d, J = 11.0 Hz, 1H, CH*H* Bn), 4.79 (d, J = 10.8 Hz, 1H, C*H*H Bn), 4.72 (d, J = 11.6 Hz, 1H, C*H*H Bn), 4.62 (d, J = 11.6 Hz, 1H, CH*H* Bn), 4.57 (d, J = 10.8 Hz, 1H, CH*H* Bn), 4.02 (d, J = 4.4 Hz, 1H, H-1), 3.84 (d, J = 9.4 Hz, 1H, H-5), 3.70 (s, 3H, CH_3 COOMe), 3.75 – 3.64 (m, 3H, H-2, H-3, H-4); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 169.8 (C=O), 138.6, 138.1, 137.9 ($C_{q\text{-}arom}$), 128.7, 128.6, 128.5, 128.1, 128.1, 128.0, 128.0, 128.0, 127.9 (CH_{arom}), 85.3 (C-3), 79.5 (C-4), 78.7 (C-5), 77.7 (C-2), 75.7, 75.3, 73.6 (CH_2 Bn), 68.0 (t, J = 21.1 Hz, C-1), 52.6 (CH_3 COOMe); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.26 (D-1); HRMS: $[M+Na]^+$ calcd for $C_{28}H_{29}DO_6Na$ 486.1997, found 486.2004.



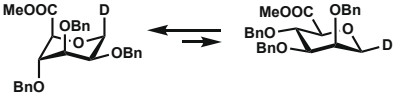
1-Deutero-1,2-di-deoxy-3,4,6-tri-*O*-benzyl-D-glucopyranoside (S49). The title compound was prepared according to general procedure VI yielding compound **S49** (32 mg, 76 µmol, 76%, colorless oil, 1,3-*cis*:1,3-*trans*; 52:48). TLC: R_f 0.62 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 734, 1027, 1086, 1360, 1452, 2862, 2922; Data of the major stereoisomer (1,3-*cis* product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.40 – 7.11 (m, 15H, CH_{arom}), 4.90 (d, J = 10.8 Hz, 1H, C*H*H Bn), 4.70 (d, J = 11.7 Hz, 1H, C*H*H Bn), 4.63 (d, J = 10.3 Hz, 1H, CH*H* Bn), 4.60 (d, J = 10.8 Hz, 1H, C*H*H Bn), 4.53 (d, J = 12.2 Hz, 1H, CH*H* Bn), 4.52 (d, J = 10.8 Hz, 1H, CH*H* Bn), , 3.72 – 3.59 (m, 3H, H-3, H-6, H-6), 3.49 (t, J = 9.1 Hz, 1H, H-4), 3.39 – 3.31 (m, 1.52H, H-1, H-5), 2.07 (ddd, J = 13.0, 5.0, 1.9 Hz, 1H, H-2_{eq}), 1.70 (dddd, J = 16.3, 12.9, 9.5, 3.9 Hz, 1H, H-2_{ax}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.7, 138.6, 138.2 ($C_{q\text{-}arom}$), 128.5, 128.5, 128.5, 128.1, 128.1, 127.8, 127.7, 127.7 (CH_{arom}), 81.3 (C-3), 79.4 (C-5), 78.6 (C-4), 75.2, 73.7, 71.5 (CH_2 Bn), 69.6 (C-6), 65.5 (t, J = 22.5 Hz, C-1), 31.5 (C-2); ^{2}H NMR (77 MHz, $CHCl_3$): δ 4.05 (D-1); Data of the minor stereoisomer (1,3-*trans* product): ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): 3.98 (dd, J = 5.0, 1.7 Hz, 0.48 H, H-1'); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 65.5 (t, J = 22.5 Hz, C-1); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.36 (D-1'); HRMS: $[M+Na]^+$ calcd for $C_{27}H_{29}DO_4Na$ 442.2099, found 442.2103.



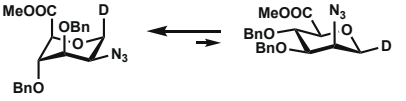
1-Deutero-2-azido-1,2-di-deoxy-3,4,6-tri-*O*-benzyl-1-α-D-glucopyranoside (S50). The title compound was prepared according to general procedure VI yielding compound **S50** (24 mg, 52 µmol, 52%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.77 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{25}$ −9.2° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 697, 735, 1027, 1059, 1109, 1137, 1261, 1362, 1454, 1497, 2104, 2866; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.51 – 6.88 (m, 15H, CH_{arom}), 4.88 (s, 2H, CH_2 Bn), 4.80 (d, J = 10.8 Hz, 1H, C*H*H Bn), 4.60 (d, J = 12.1 Hz, 1H, C*H*H Bn), 4.52 (d, J = 10.8 Hz, 1H, CH*H* Bn), 4.51 (d, J = 12.1 Hz, 1H, CH*H* Bn), 4.01 (d, J = 5.4 Hz, 1H, H-1), 3.71 – 3.57 (m, 4H, H-2, H-4, H-6, H-6), 3.51 (dd, J = 9.5, 8.9 Hz, 1H, H-3), 3.36 (ddd, J = 9.7, 4.1, 2.3 Hz, 1H, H-5); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.0, 137.9, 137.9 ($C_{q\text{-}arom}$), 128.6, 128.6, 128.6, 128.3, 128.1, 128.1, 128.0, 128.0, 127.9 (CH_{arom}), 85.5 (C-3), 79.7 (C-5), 78.3 (C-4), 75.7, 75.2, 73.7 (CH_2 Bn), 68.8 (C-6), 68.0 (t, J = 21.5 Hz, C-1), 61.9 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{27}H_{28}DN_3NaO_4$ 483.2113, found 483.2118.



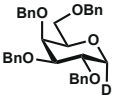
1-Deutero-1-deoxy-2,3,4,6-tetra-*O*-benzyl-β-D-mannopyranoside (S51). The title compound was prepared according to general procedure VI yielding compound **S51** (49 mg, 93 µmol, 93%, colorless oil, 1,2-*cis*:1,2-*trans*; 97:3). TLC: R_f 0.60 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{20}$ –28.3° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 699, 723, 1020, 1090, 1128, 1356, 1454, 1498, 2860; Data of the major stereoisomer (1,2-*cis* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.66 – 7.03 (m, 20H, CH_{arom}), 4.92 (d, *J* = 10.8 Hz, 1H, C*H*H Bn), 4.80 (d, *J* = 12.6 Hz, 1H, C*H*H Bn), 4.65 (d, *J* = 12.4 Hz, 1H, C*H*H Bn), 4.63 – 4.54 (m, 4H, C*H*H Bn, CH*H* Bn, CH*H* Bn, CH*H* Bn), 4.52 (d, *J* = 10.8 Hz, 1H, CH*H* Bn), 3.89 (t, *J* = 9.4 Hz, 1H, H-4), 3.79 – 3.64 (m, 3H, H-2, H-6, H-6), 3.57 (dd, *J* = 9.3, 3.3 Hz, 1H, H-3), 3.42 (ddd, *J* = 9.6, 5.9, 2.1 Hz, 1H, H-5), 3.27 (s, 0.95H, H-1); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 138.5, 138.4, 138.3, 138.3 ($C_{q\text{-}arom}$), 129.4, 128.5, 128.5, 128.4, 128.4, 128.1, 128.1, 128.0, 127.8, 127.7, 127.7 (CH_{arom}), 82.9 (C-3), 79.8 (C-5), 75.4 (CH_2 Bn), 75.3 (C-4), 73.6 (CH_2 Bn), 72.3 (C-2), 71.6, 71.0 (CH_2 Bn), 69.8 (C-6), 66.5 (t, *J* = 22.2 Hz, C-1); Data of the minor stereoisomer (1,2-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 4.11 (d, *J* = 2.3 Hz, 0.05 H); HRMS: $[M+Na]^+$ calcd for $C_{34}H_{35}NaDO_5$ 548.2518, found 548.2521.



Methyl (2,3,4-tri-*O*-benzyl-1-deoxy-β-deuterio-D-mannopyranosyl uronate) (S52). The title compound was prepared according to general procedure VI yielding compound **S52** (35 mg, 76 µmol, 76%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.72 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{25}$ –8.3° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 696, 735, 1027, 1091, 1104, 1205, 1454, 1750, 2869; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.80 – 7.15 (m, 15H, CH_{arom}), 4.66 (s, 2H, CH_2 Bn), 4.62 (d, *J* = 12.2 Hz, 1H. C*H*H Bn), 4.60 – 4.52 (m, 3H, C*H*H Bn, CH*H* Bn, CH*H* Bn), 4.26 (dd, *J* = 6.3, 4.9 Hz, 1H, H-4), 4.13 (d, *J* = 4.8 Hz, 1H, H-5), 3.88 (t, *J* = 3.2 Hz, 1H, H-2), 3.74 (dd, *J* = 6.1, 2.9 Hz, 1H, H-3), 3.63 (s, 3H, CH_3 COOMe), 3.58 (d, *J* = 3.5 Hz, 1H, H-1); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 170.0 (C=O), 138.3, 138.2, 138.0 ($C_{q\text{-}arom}$), 131.2, 128.6, 128.5, 128.4, 128.0, 128.0, 127.9, 127.8, 127.8, 127.8, 124.9 (CH_{arom}), 76.7 (C-3), 76.2 (C-4), 75.4 (C-5), 73.6, 72.2 (CH_2 Bn), 71.9 (C-2), 71.4 (CH_2 Bn), 63.7 (td, *J* = 21.5 Hz, C-1), 52.3 (CH_3 COOMe); ^2H NMR (77 MHz, $CHCl_3$): δ 4.21 (D-1); HRMS: $[M+Na]^+$ calcd for $C_{28}H_{29}DO_6Na$ 486.1997, found 486.1998.

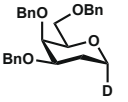


Methyl (2-azido-3,4-di-*O*-benzyl-1,2-dideoxy-β-deuterio-D-glucopyranosyl uronate) (S53). The title compound was prepared according to general procedure VI yielding compound **S53** (21 mg, 53 µmol, 53%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.56 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{25}$ –4.1° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 698, 738, 1026, 1100, 1133, 1278, 1454, 1750, 2102, 2880; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.38 – 7.24 (m, 10H, CH_{arom}), 4.68 (s, 2H, CH_2 Bn), 4.61 (s, 2H, CH_2 Bn), 4.20 (dd, *J* = 6.0, 5.0 Hz, 1H, H-4), 4.13 (d, *J* = 5.0 Hz, 1H, H-5), 3.84 – 3.76 (m, 2H, H-2, H-3), 3.65 (d, *J* = 1.5 Hz, 1H, H-1), 3.59 (s, 3H, CH_3 COOMe); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 169.5 (C=O), 137.6, 137.2 ($C_{q\text{-}arom}$), 128.7, 128.6, 128.2, 128.2, 128.1, 128.0 (CH_{arom}), 77.7 (C-3), 75.1 (C-4/C-5), 75.1 (C-5/C-4), 73.7, 72.6 (CH_2 Bn), 63.7 (bs, C-1), 56.2 (C-2), 52.4 (CH_3 COOMe); HRMS: $[M+Na]^+$ calcd for $C_{21}H_{22}DN_3NaO_5$ 421.1593, found 421.1591.

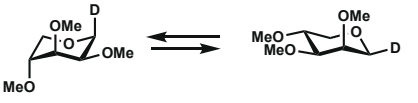


1-Deutero-1-deoxy-2,3,4,6-tetra-*O*-benzyl-α-D-galactopyranoside (S54). The title compound was prepared according to general procedure VI yielding compound **S54** (45 mg, 86 µmol, 86%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.65 (pentane:EtOAc, 8:2, v:v); $[\alpha]_D^{20}$ 1.2° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 690, 730, 1029, 1092, 1129, 1350, 1449, 1493, 2867; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 7.43 – 7.21 (m, 20H, CH_{arom}), 4.94 (d, *J* = 11.5 Hz, 1H, C*H*H Bn), 4.81 – 4.73 (m, 3H, CH*H* Bn, C*H*H Bn,

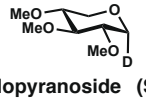
C*H*H Bn), 4.64 (d, *J* = 11.5 Hz, 1H, CH*H* Bn), 4.59 (d, *J* = 11.6 Hz, 1H, CH*H* Bn), 4.47 (d, *J* = 11.9 Hz, 1H, C*H*H Bn), 4.39 (d, *J* = 11.9 Hz, 1H, CH*H* Bn), 4.08 – 3.99 (m, 2H, H-1, H-3), 3.93 (dd, *J* = 2.9, 1.1 Hz, 1H, H-4), 3.59 – 3.50 (m, 2H, H-6, H-2), 3.49 (td, *J* = 6.0, 1.1 Hz, 1H, H-5), 3.43 (dd, *J* = 8.9, 6.1 Hz, 1H, H-6); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.7, 138.7, 138.6, 138.0 ($C_{q\text{-arom}}$), 128.5, 128.5, 128.4, 128.4, 128.1, 127.9, 127.9, 127.8, 127.7, 127.7, 127.6 (CH_{arom}), 83.8 (C-2), 78.0 (C-5), 75.3 (C-3), 74.8 (CH_2 Bn), 74.5 (C-4), 73.7, 73.7, 72.8 (CH_2 Bn), 69.4 (C-6), 68.3 (t, *J* = 21.2 Hz, C-1); HRMS: $[M+Na]^+$ calcd for $C_{34}H_{35}NaDO_5$ 548.2518, found 548.2518.



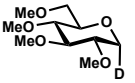
1-Deutero-1,2-di-deoxy-3,4,6-tri-*O*-benzyl-1-α-D-galactopyranoside (S55). The title compound was prepared according to general procedure VI yielding compound **S55** (38 mg, 91 µmol, 91%, colorless oil, 1,3-*cis*:1,3-*trans*; <2:98). TLC: R_f 0.52 (pentane:EtOAc, 8:2, v:v); IR (thin film, cm^{-1}): 730, 1025, 1080, 1368, 1450, 2863, 2920; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.64 – 7.05 (m, 15H, CH_{arom}), 4.93 (d, *J* = 11.7 Hz, 1H, C*H*H Bn), 4.66 – 4.56 (m, 3H, CH*H* Bn, C*H*H Bn, CH*H* Bn), 4.49 (d, *J* = 11.9 Hz, 1H, C*H*H Bn), 4.41 (d, *J* = 11.9 Hz, 1H, CH*H* Bn), 4.04 (dd, *J* = 5.0, 1.8 Hz, 1H, H-1), 3.85 (dt, *J* = 2.4, 1.1 Hz, 1H, H-4), 3.63 – 3.56 (m, 1H, H-6), 3.54 (ddd, *J* = 11.7, 4.5, 2.5 Hz, 1H, H-3), 3.50 – 3.42 (m, 2H, H-5, H-6), 2.19 (td, *J* = 12.2, 4.9 Hz, 1H, H-2_{ax}), 1.77 (ddt, *J* = 12.6, 4.5, 1.6 Hz, 1H, H-2_{eq}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 138.9, 138.6, 138.1 ($C_{q\text{-arom}}$), 128.5, 128.5, 128.4, 128.3, 128.0, 127.8, 127.7, 127.6, 127.4 (CH_{arom}), 78.6 (C-3), 78.1 (C-5), 74.4, 73.6 (CH_2 Bn), 73.4 (C-4), 70.2 (CH_2 Bn), 70.0 (C-6), 66.0 (t, *J* = 21.5 Hz, C-1), 27.3 (C-2); HRMS: $[M+Na]^+$ calcd for $C_{27}H_{29}NaDO_4$442.2099, found 442.2106.



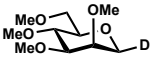
1-Deutero-1-deoxy-2,3,4-tri-*O*-methyl-D-lyxopyranoside (S56). The title compound was prepared according to general procedure VI yielding compound **S56** (16 mg, 90 µmol, 90%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.28 (pentane:EtOAc, 5:5, v:v); $[\alpha]_D^{20}$ −133.7° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 733, 953, 1072, 1096, 1357, 1462, 2824, 2897; ^{1}H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 3.88 (dd, *J* = 11.7, 3.7 Hz, 1H, H-5), 3.62 (t, *J* = 2.9 Hz, 1H, H-2), 3.54 (dt, *J* = 6.9, 3.4 Hz, 1H, H-4), 3.51 (s, 3H, CH_3), 3.47 (s, 3H, CH_3), 3.45 (m, 4H, H-1, CH_3), 3.42 (dd, *J* = 7.1, 3.2 Hz, 1H, H-3), 3.35 (dd, *J* = 11.8, 6.8 Hz, 1H, H-5); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 80.2 (C-3), 76.3 (C-4), 75.0 (C-2), 66.6 (C-5), 65.3 (t, *J* = 22.5 Hz, C-1), 58.3, 58.0, 57.4 (CH_3 Me); ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.85 (D-1); HRMS: $[M+H]^+$ calcd for $C_8H_{16}DO_4$ 178.11896, found 178.11840.



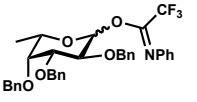
1-Deutero-1-deoxy-2,3,4-tri-*O*-methyl-D-xylopyranoside (S57). The title compound was prepared according to general procedure VI yielding compound **S57** (15 mg, 85 µmol, 85%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.62 (pentane:EtOAc, 5:5, v:v); $[\alpha]_D^{20}$ −1.8° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 841, 922, 1022, 1099, 1161, 1462, 2827, 2932; ^{1}H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 4.00 (dd, *J* = 5.0, 1.2 Hz, 1H, H-5_{eq}), 3.97 (td, *J* = 4.9, 1.2 Hz, 1H, H-1), 3.63 (s, 3H, CH_3), 3.48 (s, 6H, CH_3, CH_3), 3.26 – 3.19 (m, 2H, H-2, H-4), 3.12 (t, *J* = 8.3 Hz, 1H, H-3), 3.09 (dd, *J* = 11.2, 9.9 Hz, 1H, H-5_{ax}); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 86.0 (C-3), 79.6, 79.5 (C-2/C-4), 68.2 (C-5), 67.9 (t, *J* = 21.5 Hz, C-1), 60.7 (CH_3 Me), 58.9 (CH_3 Me, CH_3 Me; ^{2}H NMR (77 MHz, $CHCl_3$): δ 3.08 (D-1); HRMS: $[M+H]^+$ calcd for $C_8H_{16}DO_4$ 178.11896, found 178.11847.



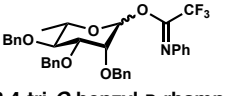
1-Deuterio-1-deoxy-2,3,4,6-tetra-*O*-methyl-α-D-glucopyranoside (S58). The title compound was prepared according to general procedure VI yielding compound **S58** (21 mg, 95 µmol, 95%, colorless oil, 1,2-*cis*:1,2-*trans*; >98:2). TLC: R_f 0.69 (pentane:EtOAc, 5:5, v:v); $[\alpha]_D^{20}$ 4.2° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 830, 920, 1031, 1086, 1464, 2821, 2940; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 4.04 (d, *J* = 5.2 Hz, 1H, H-1), 3.64 (s, 3H, CH_3), 3.60 (dd, *J* = 10.4, 2.1 Hz, 1H, H-6), 3.54 (s, 4H, CH_3, H-6), 3.47 (s, 3H, CH_3), 3.40 (s, 3H, CH_3), 3.29 – 3.18 (m, 2H, H-2, H-5), 3.18 – 3.05 (m, 2H, H-3, H-4); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 87.9 (C-3), 80.0 (C-2), 79.7 (C-4), 79.1 (C-5), 71.8 (C-6), 67.4 (t, *J* = 21.7 Hz, C-1), 60.8, 60.6, 59.4, 58.9 (CH_3); HRMS: $[M+H]^+$ calcd for $C_{10}H_{19}NaDO_5$ 244.1256, found 244.1267.



1-Deuterio-1-deoxy-2,3,4,6-tetra-*O*-methyl-β-D-mannopyranoside (S59). The title compound was prepared according to general procedure VI yielding compound **S59** (22 mg, 99 µmol, 99%, colorless oil, 1,2-*cis*:1,2-*trans*; 97:3). TLC: R_f 0.71 (pentane:EtOAc, 5:5, v:v); $[\alpha]_D^{20}$ −16.1° (*c* 1, $CHCl_3$); IR (thin film, cm^{-1}): 833, 923, 1028, 1090, 1465, 2825, 2930; Data of the major stereoisomer (1,2-*cis* product): ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): δ 3.65 (dd, *J* = 10.3, 2.0 Hz, 1H, H-6), 3.62 (dd, *J* = 3.4, 0.9 Hz, 1H, H-2), 3.56 (dd, *J* = 10.3, 6.4 Hz, 1H, H-6), 3.53 (s, 3H, CH_3), 3.50 (s, 3H, CH_3), 3.45 (s, 3H, CH_3), 3.41 (s, 3H, CH_3), 3.36 (t, *J* = 9.3 Hz, 1H, H-4), 3.31 – 3.23 (m, 2.96H, H-1, H-3, H-5); ^{13}C NMR (126 MHz, $CDCl_3$, HSQC): δ 84.6 (C-3), 79.5 (C-5), 77.0 (C-4), 75.2 (C-2), 72.4 (C-6), 65.5 (t, *J* = 22.7 Hz, C-1), 61.0, 59.4, 57.4, 57.3 (CH_3); Data of the minor stereoisomer (1,2-*trans* product): ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC, NOESY): 4.17 (d, *J* = 1.5 Hz, 0.04H); HRMS: $[M+H]^+$ calcd for $C_{10}H_{19}NaDO_5$ 244.1256, found 244.1269.

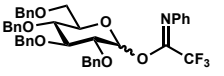


2,2,2-trifluoro-*N*-phenylacetimidoyl 2,3,4-tri-*O*-benzyl-D-fucopyranoside (S60). 2,3,4-tri-*O*-benzyl-α/β-D-fucopyranoside (87 mg, 0.2 mmol) was dissolved in acetone (2 mL, 0.1 M) and water (0.2 mL, 50 eq.) and cooled on ice. Subsequently, $CsCO_3$ (130 mg, 0.4 mmol, 1.8 eq.) and 2,2,2-trifluoro-*N*-phenylacetimidoyl chloride (83 mg, 0.4 mmol, 1.8 mmol) was added and the solution was allowed to attain room temperature After stirring for 18 h, the solution was diluted with H_2O and EtOAc. The aqueous layer was extracted (3x) with EtOAc followed by washing the combined organic layer with H_2O, sat. aq. $NaHCO_3$ and brine respectively. Subsequently, the organic layer was dried over $MgSO_4$, filtered and concentrated *in vacuo* to yield the crude product as a colorless oil. Flash column chromatography (95:5 → 80:20; pentane:Et_2O) yielded the title compound **S60** (102 mg, 0.17 mmol, 76%, α:β; 33:67) as a colorless oil. Spectroscopic data was in accordance with literature.[69] TLC: R_f 0.4 (pentane: Et_2O, 9:1, v:v); Data for the anomeric mixture: (500 MHz, Toluene-d_8, *T* = 333 K, HH-COSY, HSQC): δ 7.64 – 6.60 (m, 30H, CH_{arom}), 6.38 (s, 0.5H, H-1α), 5.54 (s, 1H, H-1β), 5.06 – 4.61 (m, 9H, CH_2 Bnα, CH_2 Bnα, CH_2 Bnα, CH_2 Bnβ, CH_2 Bnβ, CH_2 Bnβ), 4.16 (dd, *J* = 10.1, 3.5 Hz, 0.5H, H-2α), 4.08 – 3.98 (m, 1.5H, H-2β, H-5α), 3.96 (dd, *J* = 10.1, 2.8 Hz, 0.5H, H-3α), 3.67 (dd, *J* = 2.8, 1.3 Hz, 0.5H, H-4α), 3.63 – 3.47 (m, 2H, H-3β, H-4β), 3.41 (s, 1H, H-5β), 1.18 (m, 4.5H, $CH_{3α}$, $CH_{3β}$); ^{13}C NMR (101 MHz, Toluene-d_8, *T* = 333 K, HSQC): δ 144.1, 144.0, 138.9, 138.7, 138.7, 138.6, 138.5, 135.4 ($C_{q\text{-}arom}$), 129.5, 128.8, 128.7, 128.6, 128.5, 128.5, 128.5, 128.4, 128.3, 127.9, 127.8, 127.8, 127.8, 127.7, 126.6, 124.3, 124.2, 120.8, 119.8, 119.6 (CH_{arom}), 98.0 (C-1β), 95.4 (bs, C-1α), 82.8 (C-3β), 78.9 (C-3α), 78.4 (C-2β), 78.0 (C-4α), 76.7 (C-4β), 76.0 (C-2α), 75.5, 75.2, 75.1, 73.6, 73.6, 73.5 (CH_2 Bn), 71.9 (C-5β), 69.9 (C-5α), 16.8 ($CH_{3β}$), 16.8 ($CH_{3α}$).



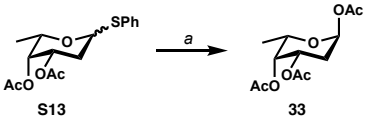
2,2,2-trifluoro-*N*-phenylacetimidoyl 2,3,4-tri-*O*-benzyl-D-rhamnopyranoside (S61). 2,3,4-tri-*O*-benzyl-α/β-D-rhamnopyranoside (87 mg, 0.2 mmol) was dissolved in acetone (2 mL, 0.1 M) and water (0.2 mL, 50

eq.) and cooled on ice. Subsequently, $CsCO_3$ (130 mg, 0.4 mmol, 1.8 eq.) and 2,2,2-trifluoro-*N*-phenylacetimidoyl chloride (83 mg, 0.4 mmol, 1.8 mmol) was added and the solution was allowed to attain room temperature After stirring for 18 h, the solution was diluted with H_2O and EtOAc. The aqueous layer was extracted (3x) with EtOAc followed by washing the combined organic layer with H_2O, sat. aq. $NaHCO_3$ and brine respectively. Subsequently, the organic layer was dried over $MgSO_4$, filtered and concentrated *in vacuo* to yield the crude product as a colorless oil. Flash column chromatography (95:5 → 80:20; pentane:Et_2O) yielded the title compound **S60** (109 mg, 0.18 mmol, 81%, α:β; 71:29) as a colorless oil. Spectroscopic data was in accordance with literature.[69] TLC: R_f 0.4 (pentane: Et_2O, 9:1, v:v); Data for the anomeric mixture: (500 MHz, Toluene-d_8, T = 333 K, HH-COSY, HSQC): δ 7.74 – 6.66 (m, 28H, CH_{arom}), 6.09 (bs, 1H, H-1$_\alpha$), 5.52 (bs, 0.4H, H-1$_\beta$), 4.96 – 4.46 (m, 8.4H, CH_2 Bn$_\alpha$, CH_2 Bn$_\alpha$, CH_2 Bn$_\alpha$, CH_2 Bn$_\beta$, CH_2 Bn$_\beta$, CH_2 Bn$_\beta$), 4.05 (d, J = 2.9 Hz, 0.4H, H-3$_\beta$), 3.91 – 3.72 (m, 3H, H-2$_\alpha$, H-3$_\alpha$, H-5$_\alpha$), 3.74 – 3.58 (m, 1.4H, H-2$_\beta$, H-4$_\alpha$), 3.48 (d, J = 9.1 Hz, 0.4H, H-4$_\beta$), 3.25 (bs, 0.4H, H-5$_\beta$), 1.34 (m, 4.2H, $CH_{3\alpha}$, $CH_{3\beta}$); ^{13}C NMR (101 MHz, Toluene-d_8, T = 333 K, HSQC): δ 143.9, 138.7, 138.5, 138.1 ($C_{q\text{-}arom}$), 129.6, 128.9, 128.9, 128.6, 128.5, 128.5, 128.4, 128.4, 128.2, 128.2, 128.1, 128.0, 127.9, 127.9, 127.8, 127.8, 126.6, 124.5, 120.8, 119.7, 119.6 (CH_{arom}), 96.5 (C-1$_\beta$), 96.2 (C-1$_\alpha$), 82.4 (C-4$_\beta$), 80.1 (C-4$_\alpha$), 79.9 (C-2$_\beta$), 79.3 (C-2$_\alpha$), 75.6, 75.5, 74.4 (CH_2 Bn), 74.2 (C-3$_\alpha$), 73.7 (C-3$_\beta$), 73.2 (C-5$_\beta$), 73.1, 72.9, 72.4 (CH_2 Bn), 71.3 (C-5$_\alpha$), 18.2 ($CH_{3\alpha}$), 18.1 ($CH_{3\beta}$).



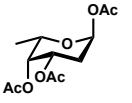
2,2,2-trifluoro-*N*-phenylacetimidoyl 2,3,4-tri-*O*-benzyl-D-rhamnopyranoside (S62). 2,3,4-tri-*O*-benzyl-α/β-D-rhamnopyranoside (108 mg, 0.2 mmol) was dissolved in acetone (2 mL, 0.1 M) and water (0.2 mL, 50 eq.) and cooled on ice. Subsequently, $CsCO_3$ (130 mg, 0.4 mmol, 1.8 eq.) and 2,2,2-trifluoro-*N*-phenylacetimidoyl chloride (83 mg, 0.4 mmol, 1.8 mmol) was added and the solution was allowed to attain room temperature After stirring for 18 h, the solution was diluted with H_2O and EtOAc. The aqueous layer was extracted (3x) with EtOAc followed by washing the combined organic layer with H_2O, sat. aq. $NaHCO_3$ and brine respectively. Subsequently, the organic layer was dried over $MgSO_4$, filtered and concentrated *in vacuo* to yield the crude product as a colorless oil. Flash column chromatography (95:5 → 80:20; pentane:Et_2O) yielded the title compound **S60** (142 mg, 197 µmol, 98%, α:β; 50:50) as a colorless syrup. Spectroscopic data was in accordance with literature.[70] TLC: R_f 0.4 (pentane: Et_2O, 9:1, v:v); Data for the anomeric mixture: (500 MHz, Toluene-d_8, T = 333 K, HH-COSY, HSQC) δ 7.78 – 6.70 (m, 50H, CH_{arom}), 6.44 (bs, 1H, H-1$_\alpha$), 5.59 (bs, 1H, H-1$_\beta$), 4.99 – 4.49 (m, 16H, CH_2 Bn$_\alpha$, CH_2 Bn$_\alpha$, CH_2 Bn$_\alpha$, CH_2 Bn$_\alpha$, CH_2 Bn$_\beta$, CH_2 Bn$_\beta$, CH_2 Bn$_\beta$, CH_2 Bn$_\beta$), 4.06 (t, J = 9.3 Hz, 1H, H-4$_\alpha$), 3.99 (m, 1H, H-6$_\alpha$), 3.80 – 3.32 (m, 10H, H-2$_\alpha$, H-3$_\alpha$, H-5$_\alpha$, H-6$_\alpha$, H-2$_\beta$, H-3$_\beta$, H-4$_\beta$, H-5$_\beta$, H-6$_\beta$, H-6$_\beta$); ^{13}C NMR (101 MHz, Toluene-d_8, T = 333 K, HSQC): δ 143.9, 143.7, 143.4, 138.9, 138.7, 138.3, 138.2, 138.1, 138.1, 135.9, 135.8, 133.5, 133.5, 133.2, 133.2 ($C_{q\text{-}arom}$), 129.4, 128.8, 128.5, 128.5, 128.4, 128.4, 128.2, 128.1, 128.0, 128.0, 127.9, 127.9, 127.9, 127.8, 127.9, 127.90, 127.80, 127.7, 127.7, 127.6, 126.7, 126.7, 126.4, 126.1, 126.0, 126.0, 124.4, 124.3, 120.7, 119.6, 119.6 (CH_{arom}), 97.6 (C-1$_\beta$), 93.9 (C-1$_\alpha$), 84.7, 81.7, 81.2, 79.7, 77.6, 77.6, 76.0, 75.7, 75.6, 75.3, 75.0, 75.0, 73.7, 73.6, 73.5, 73.5, 68.6.

Preparation of Donor 33



S13 **33**

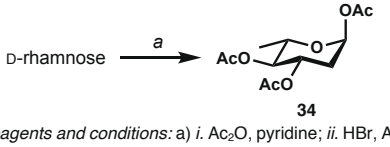
Scheme S5. Donor **33** synthesis. *Reagents and conditions:* a) NIS, AcOH, Et_2O, 1,2-dichloroethane, **33**: 67%.



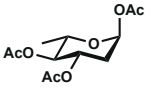
Acetyl 3,4-di-*O*-acetyl-2-deoxy-α-L-fucopyranoside (33). Glacial acetic acid (11.9 mL, 208 mmol, 100 eq.) was added to a mixture of NIS (0.52 g, 2.29 mmol, 1.1 eq.) in Et_2O (10.4 mL) and 1,2-dichloroethane (10.4 mL). The formed solution was added to compound **S13** (0.69 g, 2.1 mmol). After 45 min of stirring,

the reaction was quenched with sat. aq. NaS_2O_3. The aqueous mixture was extracted with DCM (3x), dried over $MgSO_4$ and concentrated *in vacuo*. Column chromatography (pentane:EtOAc, 10:90 → 70:30) was performed to yield title compound **33** as an 1:4 1,3-*cis*/1,3-*trans* mixture (0.49 g, 1.8 mmol, 86%, colorless oil). Additional purification by column made it possible to solely isolate the 1,3-*trans* product (0.38 g, 1.4 mmol, 67%, colorless solid). TLC: R_f 0.45 (pentane:EtOAc, 3:7, v:v); IR (neat, cm^{-1}): 802, 927, 987, 1011, 1038, 1194, 1222, 1368, 1441, 1739; Data for the major stereoisomer (1,3-*trans* product): ^1H NMR (400 MHz, $CDCl_3$, HH-COSY, HSQC): δ 6.32 (d, *J* = 2.7 Hz, 1H, H-1), 5.32 (ddd, *J* = 12.5, 5.1, 3.0 Hz, 1H, H-3), 5.28 – 5.22 (m, 1H, H-4), 4.20 (q, *J* = 6.5 Hz, 1H, H-5), 2.21 (td, *J* = 13.0, 3.6 Hz, 1H, H-2), 2.20 (s, 3H, CH_3 Ac), 2.14 (s, 3H, CH_3 Ac), 2.04 (s, 3H, CH_3 Ac), 1.91 (ddt, *J* = 13.4, 5.1, 1.2 Hz, 1H, H2), 1.18 (d, *J* = 6.5 Hz, 3H, H-6, H-6, H-6); ^{13}C NMR (101 MHz, $CDCl_3$, HSQC): δ 170.8, 170.3, 169.5 (C=O Ac), 92.1 (C-1), 69.4 (C-4), 67.5 (C-5), 66.4 (C-3), 28.9 (C-2), 21.3, 21.1, 20.9 (CH_3 Ac), 16.7 (C-6); HRMS: $[M+Na]^+$ calcd for $C_{12}H_{18}NaO_7$ 297.09447, found 297.09439.

Preparation of donor 34



Scheme S6. Donor **34** synthesis. *Reagents and conditions:* a) *i.* Ac_2O, pyridine; *ii.* HBr, AcOH, DCM; *iii.* $CuSO_4{\cdot}5H_2O$, Ac_2O, NaOAc, AcOH, Zn; *iv.* Ac_2O, HBr, AcOH, **34**: 60%.



2-deoxy-1,3,4-tri-*O*-acetyl-α-L-rhamnopyranoside (34). To suspension of L-rhamnose (4.5 g, 27.5 mmol) in pyridine (25 mL), Ac_2O (32 mL, 340 mmol, 12 eq.) at 0 °C. After stirring for an additional 16 h at room temperature. The mixture was concentrated *in vacuo* and co-evaporated three times with heptane. The resulting colorless oil was used in the next step without further purification. The crude product was dissolved in DCM (18 mL), followed by the addition of Ac_2O (1 mL, 10.6 mmol, 0.4 eq.). To the solution HBr (33 wt% in AcOH, 8.5 mL, 55.0 mmol, 2.0 eq.) was added dropwise at 0 °C and stirred for an additional 4 h at room temperature. The mixture was then concentrated under reduced pressure and the yellow oil was used as a crude product in the next step. $CuSO_4{\cdot}5H_2O$ (0.88 g), Ac_2O (3.6 mL, 38 mmol, 1.4 eq.), sodium acetate (4.5 g, 55 mmol, 2 eq.), AcOH (3.2 mL) were suspended in acetonitrile (12 mL), and subsequently Zn (dust, 3.6 g, 55 mmol, 2 eq.) was added. After 45 min of stirring the rhamnosyl bromide was added in 60 mL acetonitrile via a dropping funnel over 40 min. The reaction was allowed to stir for an additional 2 h. After reaction completion the mixture was diluted with DCM and filtrated over Celite® 545 (Sigma-Aldrich) and transferred to a separatory funnel. The organic phase was washed with saturated sat. aq. $NaHCO_3$, dried with $MgSO_4$ and concentrated *in vacuo*. The crude rhamnal was dissolved in DCM (40 mL) and AcOH (15.8 mL, 276 mmol, 10 eq.), Ac_2O (22.2 mL, 233 mmol, 8.5 eq.) were added at 0 °C. After 15 min stirring, HBr (33 wt% in AcOH, 1.5 mL, 9.1 mmol, 0.3 eq.) was dropwise added at 0 °C and the reaction was stirred for an additional 5 h. After reaction completion the mixture was quenched with ice-cold water and extracted DCM (3x). The combined organic layers were washed with sat. aq. $NaHCO_3$, dried with $MgSO_4$ and concentrated *in vacuo*. Column chromatography (95:5 → 85:15, pentane:EtOAc) gave the title compound **34** (4.5 g, 16.4 mmol, 60% over 4 steps, average of 88% per step, white solid). TLC: R_f 0.26 (pentane:EtOAc, 8:2, v:v). IR (neat, cm^{-1}): 922, 1037, 1134, 1157, 1369, 1732, 2994; ^1H NMR (500 MHz, $CDCl_3$, HH-COSY, HSQC): δ 6.19 (dd, *J* = 3.8, 1.4 Hz, 1H, H-1), 5.27 (ddd, *J* = 11.6, 9.5, 5.3 Hz, 1H, H-3), 4.80 (t, *J* = 9.7 Hz, 1H, H-4), 3.94 (dq, *J* = 9.8, 6.2 Hz, 1H, H-5), 2.26 (ddd, *J* = 13.5, 5.3, 1.5 Hz, 1H, H-2), 2.12 (s, 3H, CH_3 Ac), 2.07 (s, 3H, CH_3 Ac), 2.03 (s, 3H, CH_3 Ac), 1.92 (ddd, *J* = 13.5, 11.7, 3.7 Hz, 1H, H-2), 1.19 (d, *J* = 6.3 Hz, 3H, CH_3); ^{13}C NMR (126 MH, $CDCl_3$, HSQC): δ 170.4, 170.1, 169.3 (C=O, Ac), 90.9 (C-1), 74.2 (C-4), 68.5 (C-3), 68.3 (C-5), 34.3 (C-2), 21.2, 21.1, 20.9 (CH_3 Ac), 17.7 (CH_3); HRMS: $[M+Na]^+$ calcd for $C_{12}H_{18}NaO_7$ 297.0950, found 297.0951.

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