Institut für Chemie
Organische Chemie

Synthesis and Transformations of 2-Thiocarbohydrates:

A Practical Approach for Functionalization of Thiosugars

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Publication based on this thesis

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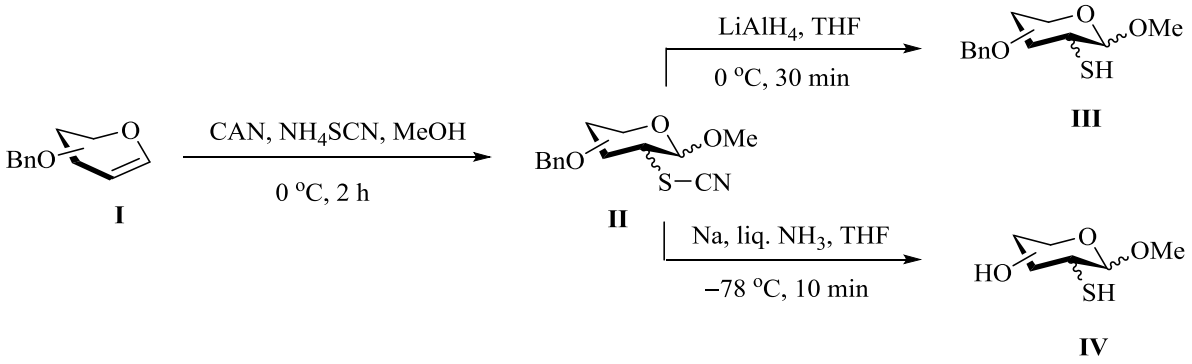
Abstract

I. Ceric ammonium nitrate (CAN) mediated thiocyanate radical additions to glycals

In this dissertation, a facile entry was developed for the synthesis of 2-thiocarbohydrates and their transformations. Initially, CAN mediated thiocyanation of carbohydrates was carried out to obtain the basic building blocks (2-thiocyanates) for the entire studies. Subsequently, 2-thiocyanates were reduced to the corresponding thiols using appropriate reagents and reaction conditions. The screening of substrates, stereochemical outcome and the reaction mechanism are discussed briefly (Scheme I).

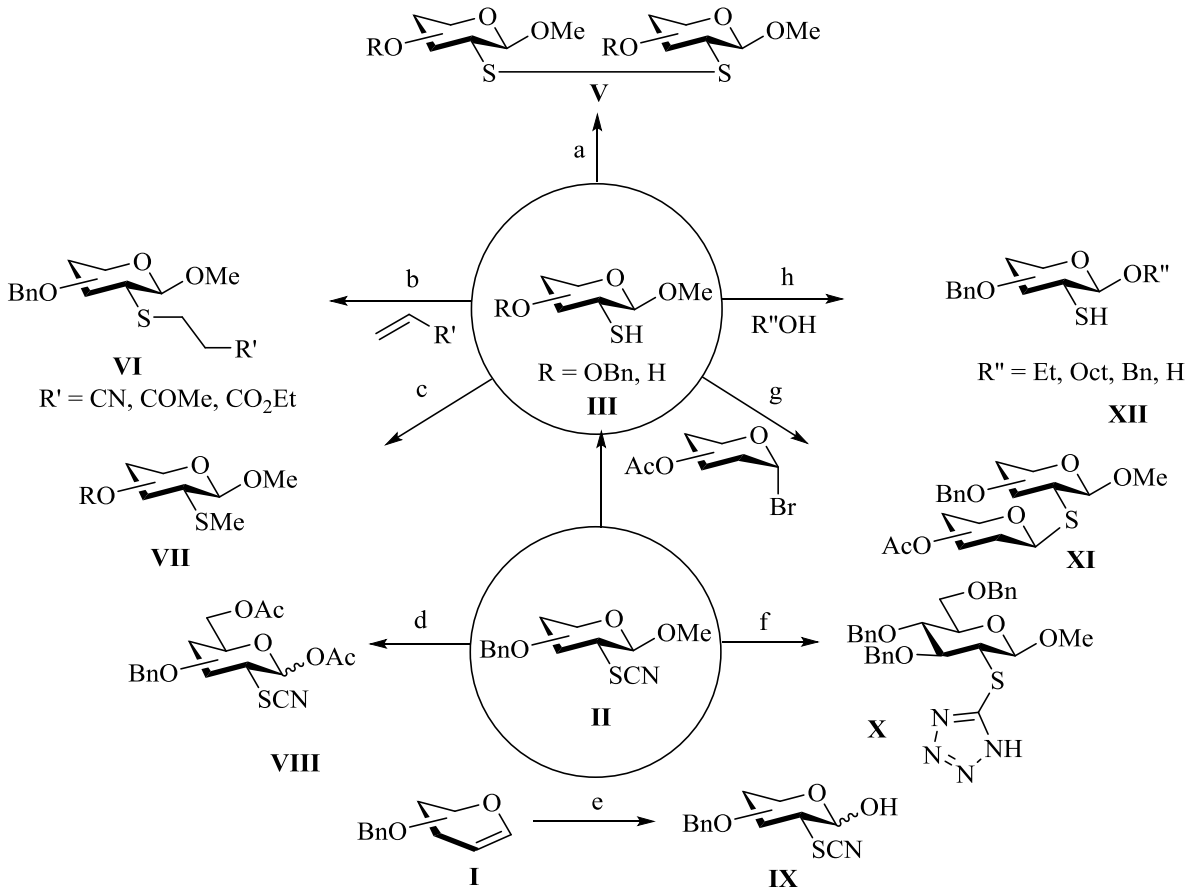


Scheme I. Synthesis of the 2-thiocyanates **II** and reductions to 2-thiols **III** & **IV**.

An interesting mechanism was proposed for the reduction of 2-thiocyanates **II** to 2-thiols **III** *via* formation of a disulfide intermediate. The water soluble free thiols **IV** were obtained by cleaving the thiocyanate and benzyl groups in a single step. In the subsequent part of studies, the synthetic potential of the 2-thiols was successfully expanded by simple synthetic transformations.

II. Transformations of the 2-thiocarbohydrates

The 2-thiols were utilized for convenient transformations including sulfa-Michael additions, nucleophilic substitutions, oxidation to disulfides and functionalization at the anomeric position. The diverse functionalizations of the carbohydrates at the C-2 position by means of the sulfur linkage are the highlighting feature of these studies. Thus, it creates an opportunity to expand the utility of 2-thiocarbohydrates for biological studies.



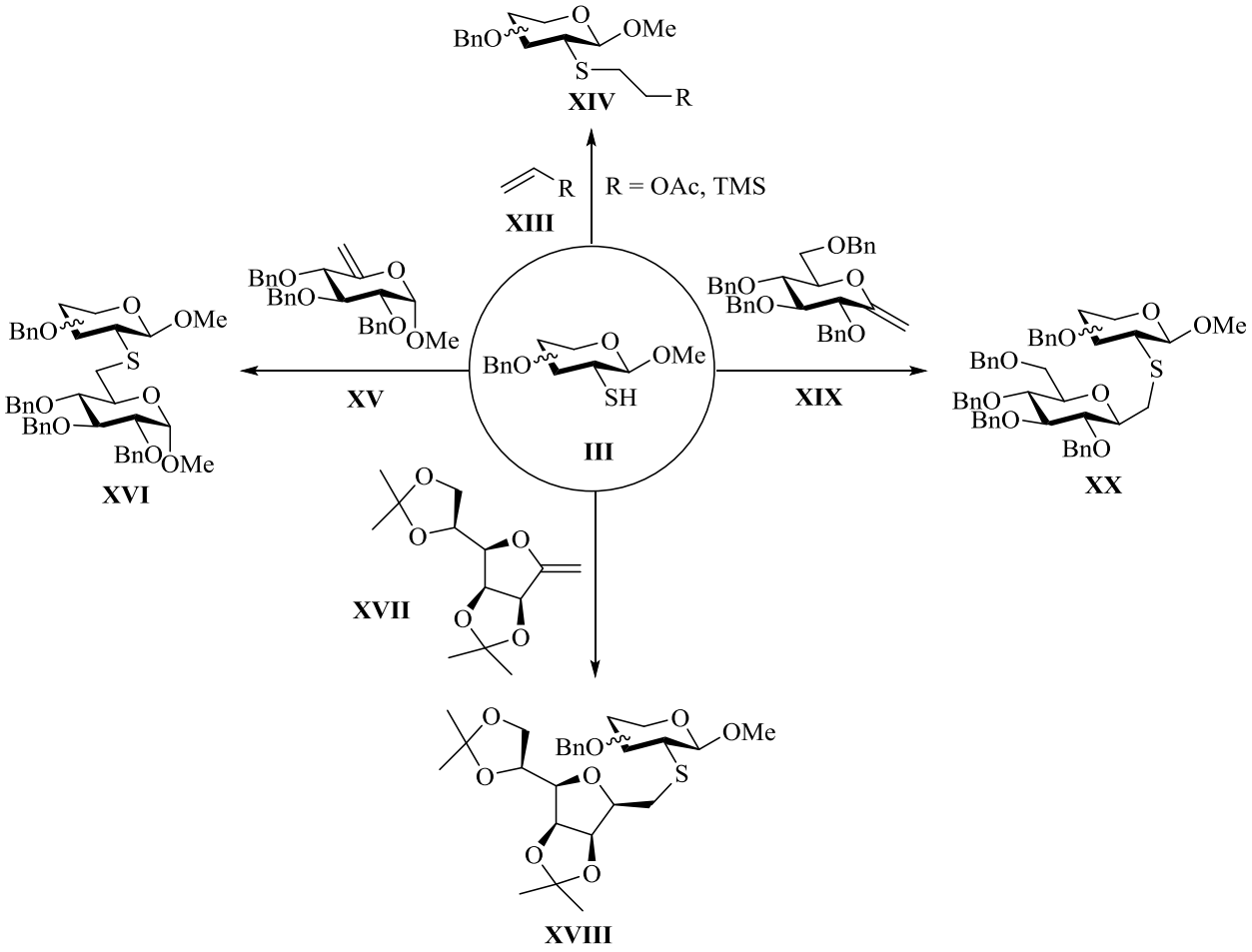
Reagents and conditions: a) I_2, pyridine, THF, rt, 15 min; b) K_2CO_3, MeCN, rt, 1 h; c) MeI, K_2CO_3, DMF, 0 °C, 5 min; d) Ac_2O, H_2SO_4 (1 drop), rt, 10 min; e) CAN, MeCN/H_2O, NH_4SCN, rt, 1 h; f) NaN_3, $ZnBr_2$, ^{i}PrOH/H_2O, reflux, 15 h; g) NaOH (1 M), TBAI, benzene, rt, 2 h; h) $ZnCl_2$, $CHCl_3$, reflux, 3 h.

Scheme II. Functionalization of 2-thiocarbohydrates.

These transformations have enhanced the synthetic value of 2-thiocarbohydrates for the preparative scale. Worth to mention is the Lewis acid catalyzed replacement of the methoxy group by other nucleophiles and the synthesis of the (2→1) thiodisaccharides, which were obtained with complete β-selectivity. Additionally, for the first time, the carbohydrate linked thiotetrazole was synthesized by a (3 + 2) cycloaddition approach at the C-2 position.

III. Synthesis of thiodisaccharides by thiol-ene coupling.

In the final part of studies, the synthesis of thiodisaccharides by a classical photoinduced thiol-ene coupling was successfully achieved.



Reagents and conditions: 2,2-Dimethoxy-2-phenylacetophenone (DPAP), CH_2Cl_2/EtOH, hν, rt.

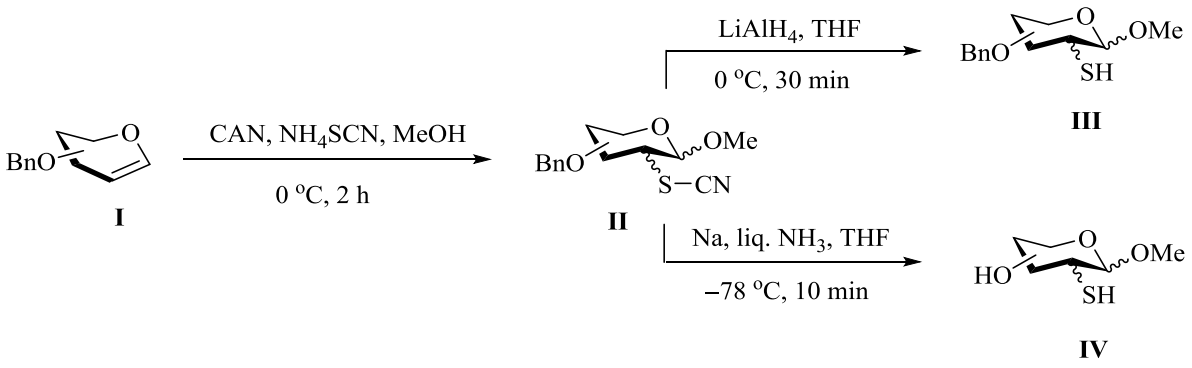
Scheme III. Thiol-ene coupling between 2-thiols and *exo*-glycals.

During the course of investigations, it was found that the steric hindrance plays an important role in the addition of bulky thiols to *endo*-glycals. Thus, we successfully screened the suitable substrates for addition of various thiols to sterically less hindered alkenes (Scheme III). The photochemical addition of 2-thiols to three different *exo*-glycals delivered excellent regio- and diastereoselectivities as well as yields, which underlines the synthetic potential of this convenient methodology.

Zusammenfassung

I. Cerammoniumnitrat (CAN) vermittelte Thiocyanat Radikaladditionen an Glycale

In dieser Dissertation wurde ein einfacher synthetischer Zugang zu 2-Thiokohlenhydraten und dessen Transformationsprodukten entwickelt. Zu Beginn wurden CAN vermittelte Funktionalisierungen von Kohlenhydraten mit Thiocyanat durchgeführt, um die notwendigen Ausgangsverbindungen (2-Thiocyanate) für die weiteren Studien zu erhalten. Im Folgenden wurden diese 2-Thiocyanate mit entsprechenden Reagenzien unter geeigneten Reduktionsbedingungen zu den Thiolen reduziert. Das Screening der Substrate, der stereochemische Verlauf und der Reaktionsmechanismus wird kurz diskutiert (Schema I).



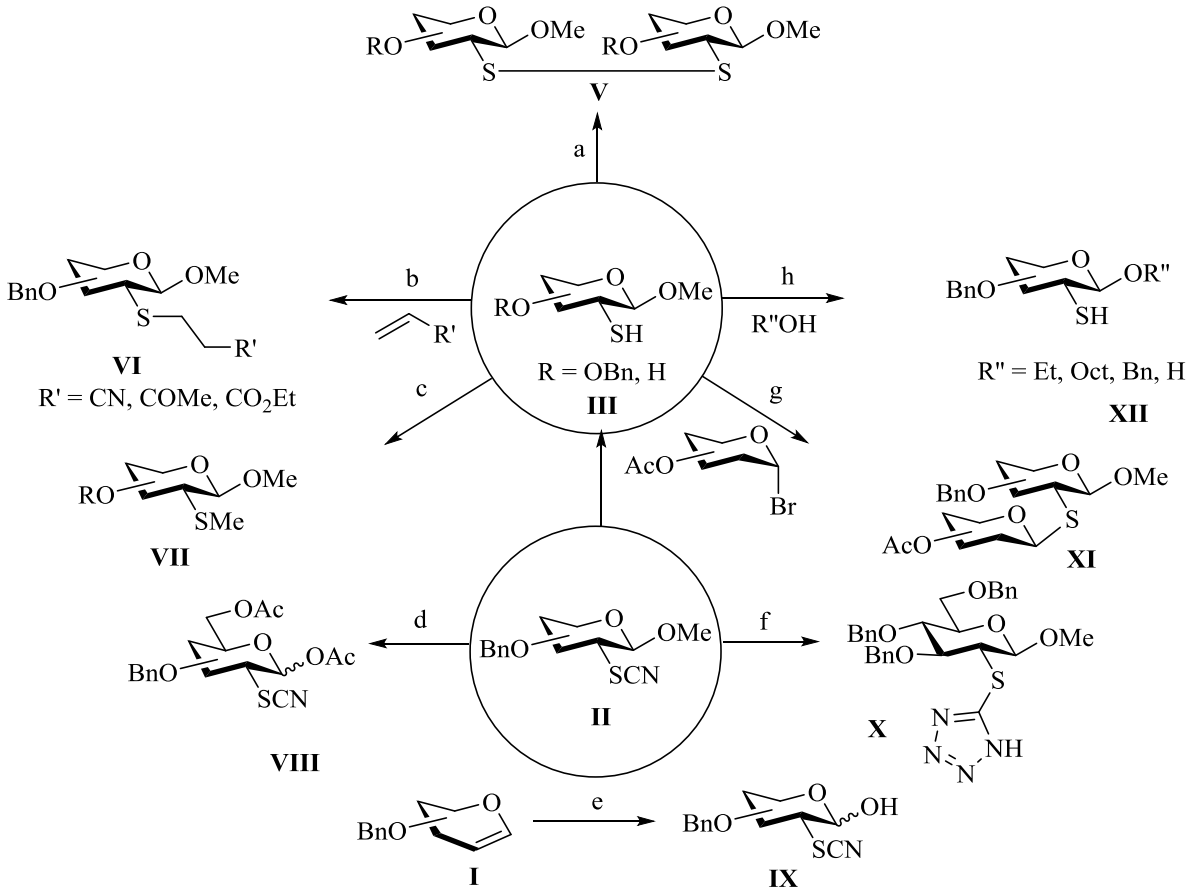
Schema I. Synthese der 2-Thiocyanate **II** und Reduktionen zu den 2-Thiolen **III** & **IV.**

Es wurde ein interessanter Mechanismus für die Reduktion der 2-Thiocyanate **II** zu den 2-Thiolen **III** *via* Bildung von Disulfid-Zwischenstufen vorgeschlagen. Die wasserlöslichen freien Thiole **IV** wurden durch Spaltung der Thiocyanat- und Benzylgruppen in einem Einzelschritt freigesetzt. Im darauf folgenden Teil der Arbeit wurde das synthetische Potenzial der 2-Tiole erfolgreich durch einfache synthetische Transformationen erweitert.

II. Transformationen der 2-Thiokohlenhydrate

Die 2-Thiole wurden für die Ausführung praktischer Transformationen eingesetzt, die Sulfa-Michael Additionen, nukleophile Substitutionen, Oxidationen zu Disulfiden und Funktionalisierungen an der anomeren Position beinhalten. Die mannigfaltigen

Funktionalisierungen der Kohlenhydrate an den C-2 Positionen mittels der Schwefel Gruppe ist das hervortretende Merkmal dieser Arbeit.



Reagenzien und Reaktionsbedingungen: a) I_2, Pyridin, THF, rt, 15 min; b) K_2CO_3, MeCN, rt, 1 h; c) MeI, K_2CO_3, DMF, 0 °C, 5 min; d) Ac_2O, H_2SO_4 (1 Tropfen), rt, 10 min; e) CAN, $MeCN/H_2O$, NH_4SCN, rt, 1 h; f) NaN_3; $ZnBr_2$; $^iPrOH/H_2O$, Rückfluss 15 h; g) NaOH (1 M), TBAI, Benzol, rt 2 h; h) $ZnCl_2$, $CHCl_3$, Rückfluss, 3 h.

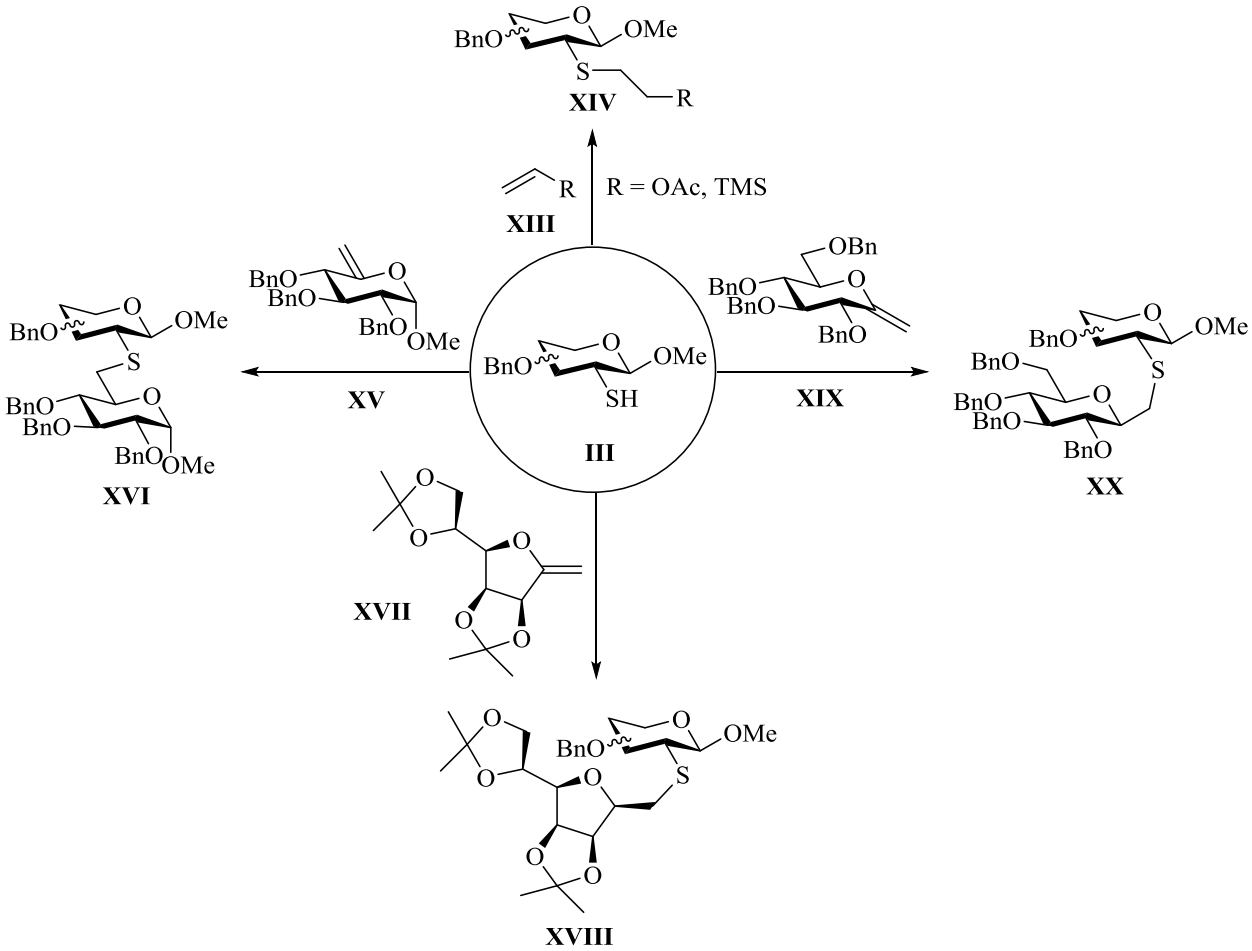
Schema II. Funktionalisierungen von 2-Thiokohlenhydraten

Daraus eröffnet sich die Möglichkeit, den Nutzwert von 2-Thiokohlenhydraten auf biologische Studien auszuweiten. Diese Transformationen haben den synthetischen Wert von 2-Thiokohlenhydraten für den präparativen Maßstab gesteigert. Hervorzuheben ist hier der Lewis

Säure katalysierte Austausch der Methoxygruppe durch weitere Nukleophile und die Synthese von (2→1) Thiodisacchariden, die mit quantitativer *β*-Selektivität erhalten wurden. Zusätzlich wurde zum ersten Mal ein Zucker gebundenes Thiotetrazol über eine (3+2) Cycloaddition an der C-2 Position synthetisiert.

III. Synthese von Thiodisacchariden durch Thiol-En-Kopplungen

Im letzten Teil der Arbeit gelang die Synthese von Thiodisacchariden durch eine klassische Thiol-En-Kopplung.



Reagenzien und Reaktionsbedingungen: 2,2-Dimethoxy-2-phenylacetophenone (DPAP), CH_2Cl_2/EtOH, h*ν*, rt.

Schema III. Thiol-En-Kopplungen zwischen 2-Thiolen und *exo*-Glycalen.

Im Verlauf der Untersuchungen wurde aufgezeigt, dass die räumlische Hinderung bei der Addition von sterisch anspruchsvollen 2-Thiolen an *endo*-Glycale eine wichtige Rolle spielt. Dazu erprobten wir geeignete Substrate zur Addition von 2-Thiolen an sterisch wenig anspruchsvolle Alkene (Schema III). Die photochemische Addition der 2-Thiole an drei verschiedene *exo*-Glycale lieferte exzellente Regio- und Diastereoselektivitäten und Ausbeuten, was das synthetische Potenzial dieser bequem durchführbaren Methodik unterstreicht.

1. Introduction

Carbohydrates, the most abundant biomolecules found in nature, are one of the highly important components for a healthy diet as they are the source of energy, which in turn support the balanced body to function and promote the physical activities. Apart from their food value, naturally occurring as well as synthetically modified carbohydrates attract a significant attention due to their diverse applications in biology, medicinal chemistry and organic chemistry.[1] Especially, functionalized sugars have emerged as very important synthetic tools for biological systems, consequently opening a wide range of opportunities for research, concerning the role of such compounds in living organisms.[2] The exclusive research in the field of carbohydrate chemistry demonstrates its unique place and comprehensive scope toward the development of new synthetic approaches. For instance, utilization of the carbohydrate motifs as chiral auxiliaries, reagents, ligands and organocatalysts became the center of attraction in synthetic organic chemistry.[3] Furthermore, carbohydrates have been employed as readily available and economically promising starting materials in the total synthesis of many natural products and biologically active compounds.[4] However, the process of structural modifications of sugars is often associated with multistep synthesis, laborious efforts and careful characterization in order to design most suitable targets for the biological studies.

The molecular diversity of carbohydrates offers excellent entries into the area of drug discovery. Therefore, in conjunction with those naturally occurring sugars, glyco-mimetics also have been explored extensively for the drug design to investigate their structural and functional influence on oligosaccharides, biomolecular scaffolds and glycoconjugates.[5] For example, glycoproteins are involved in fundamental biological processes such as cell growth, cell-cell adhesion, fertilization, viral replication and degradation of blood clots; therefore, glycobiology became an interesting field to investigate the role and mechanism of carbohydrates in the body.[6] In addition, carbohydrate mimetics are also important in the study of immunological response in microbial infections and signaling events that take place in cancer metastasis and inflammation.[7] Thus, a quick assembly of sugar mimetics can be easily accomplished with the replacement of oxygen by other atoms such as sulfur, phosphorous, carbon or nitrogen. Oligosaccharides and complex carbohydrates that are connected with an aglycon component can

be cleaved at the anomeric position by enzyme hydrolysis. In this context, particularly thioglycosides are of great interest as they act as competitive inhibitors of several glycoside hydrolases. Thio-analogs of the naturally occurring carbohydrates possess altered binding properties, consequently show an enhanced stability toward enzymatic cleavage and possible chemical degradation.[8]

2. Research background

Thioglycosides

Thioglycodides refer to the carbohydrates in which the glycosidic oxygen is replaced by sulfur; whereas, thiosugars are structurally modified carbohydrate mimics in which one or more oxygen atoms are replaced by sulfur in both furanose and pyranose forms.[9] The relative biological activity of thiosugars and conventional functionalized sugars is influenced by the structural differences such as geometry, conformation and flexibility.[10] Additionally, difference between the electronic properties of the sulfur and oxygen atoms affects the physiochemical and biological functioning in living organisms. These promising features and biological relevance of the thiosugars mark them as potential targets for carbohydrate based therapeutics.[9]

Naturally occurring thiosugars

In contrast to other naturally occurring carbohydrates, natural thiosugars are investigated with a limited access for the biological activities and biosynthetic pathways.[11] Shown in the following Figure are few examples of thiosugars found in nature. Depending on the position of the sulfur at the carbohydrate structure, they are categorized as sugar containing sulfides (endocyclic, branched and exocyclic) and free thiols (Figure 1).

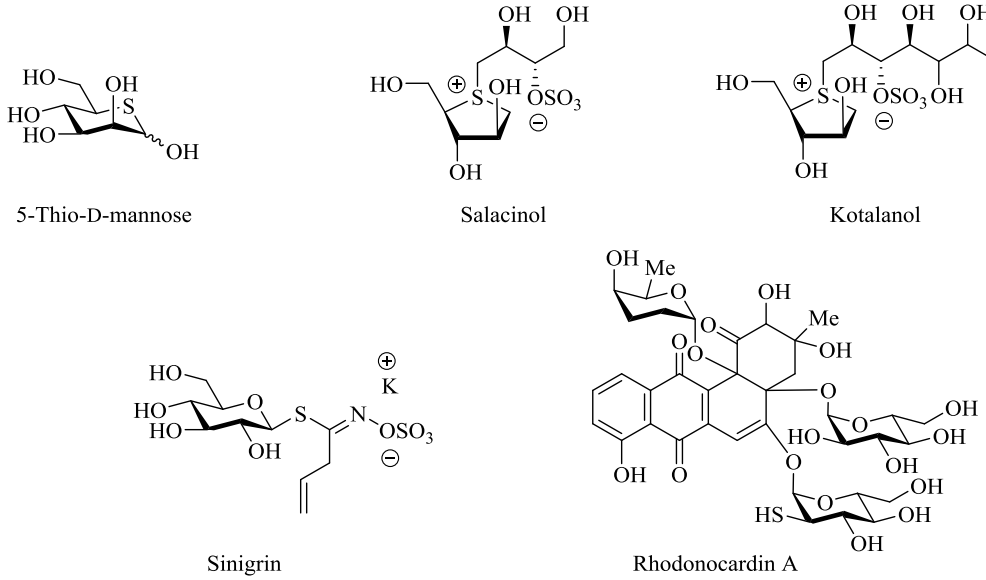


Figure 1. Naturally occurring thiosugars.

For instance, the very first example of a natural thiosugar (5-thio-D-mannose), isolated from a marine sponge *Clathria pyramida*, was reported in 1987; which was characterized by advanced analytical techniques.[12] Highly potent α-glycosidase inhibitors, namely Salacinol and Kotalanol, were isolated from the Indian herb *Salacia reticulata* WIGHT, used in traditional Ayurvedic medicine for the treatment of diabetes. These thiosugars are being examined for the therapeutic usage, considering their excellent inhibition activity against intestinal α-glycosidase.[13]

Glucosinolates are sulfur and nitrogen containing glucosides, belonging to the important class of secondary metabolites found in *Brassicaceae* and related plant families. Cruciferous or Brassica vegetables are the abundant source of glucosinolates, which can be easily detected by the pungent smell upon crushing or chewing of mustard, cabbages, radishes and broccoli. Sinigrin is one of the representative compounds amongst more than 100 glocusinolate derivatives, indicating their exclusive presence in plants. Glucosinolates undergo the breakdown upon reaction with enzyme myrosinase in the presence of water; therefore play an important role in the defense mechanism of plants by releasing glucose and other byproducts such as isothiocyanates, thiocyanates, nitriles and side chain fragments.[14]

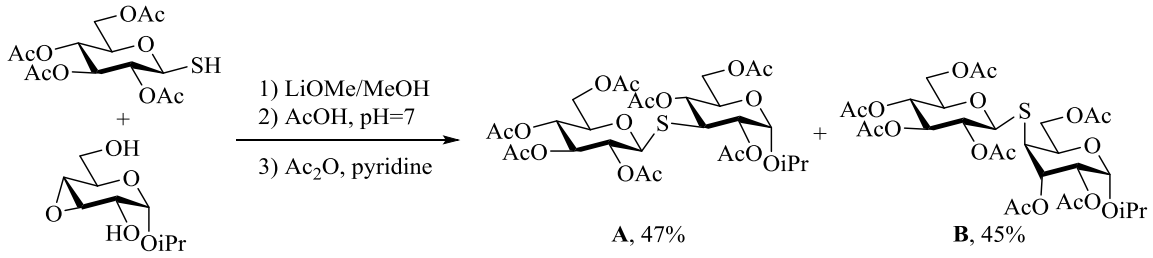
Apart from the category of thiosugars containing endocyclic thioether or branched sulfide linkage in their core structure, carbohydrates bearing free thiol groups are of the great interest. However, in comparison with a huge number of chemically synthesized sugar-thiols, Rhodonocardin A and Rhodonocardin B are the only examples of this class; specifying their negligible presence in the nature. These angucycline-type of antibiotics were isolated from a culture broth of *Nocardia* sp. No. 53 and characterized by Fukami and co-workers in 1987.[15] In contrast, synthetically modified thiosugars provide a huge library of thio-monosaccharides and thio-disaccharides, which will be discussed in the next section.

Synthesis of the thiodisaccharides

The existence of sulfur in the form of several peptides, proteins, enzymes, glycoconjugates and numerous secondary metabolites displays its importance as one of the essential elements for living systems.[16] Among the plenty of sulfur containing biomolecules, considerable efforts were invested to understand the biosynthesis of thiosugars and mechanism of the sulfur incorporation in secondary metabolites.[17] From the chemical point of view, laboratory synthesis of thiosugars

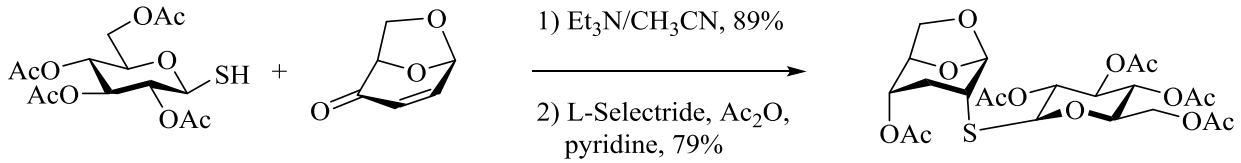
has been remained a challenging task due to the difficulties related with few significant aspects such as stereochemical control in the multistep strategies, handling of the reagents, chromatographic purification, stability of the synthesized compounds and their precise analytical characterization.

Over the past years, numerous approaches have been developed for the synthesis of sulfur containing carbohydrates. Synthesis of the thiodisaccharides can be achieved by the treatment of corresponding sugar thiols with a suitable coupling sugar counterpart. For example, the Varela group has reported a synthesis of (1→3) and (1→4) linked thiodisaccharides by using an epoxide ring opening approach.[18] A reaction of thiol with epoxide under basic conditions proceeds with the ring opening products. However, a mixture of thiodisaccharides was obtained due to the equal chances of epoxide ring opening by a corresponding thiolate at the C-3 and C-4 position, respectively (Scheme 1).



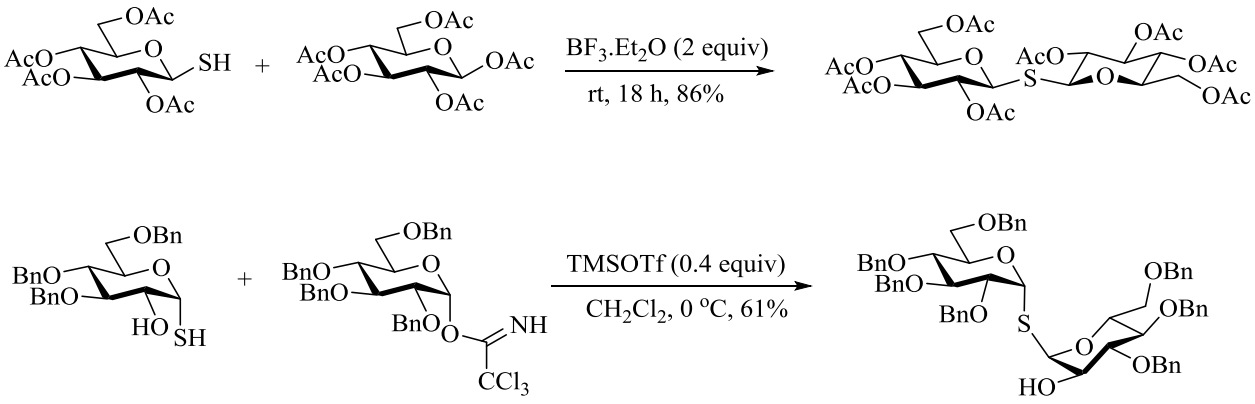
Scheme 1. Epoxide opening by a thiol-sugar.

Contrary to the hydroxyl or amino sugars, thiol-sugars have been hardly employed for additions to the sugar derived Michael acceptors. Shown in the Scheme 2, a conjugate addition based approach for the synthesis of (1→2) linked thiodisaccharides was reported by Witczak *et al.*[19] Addition of the thiol to enone followed by acetylation affords a 3-deoxy thiodisaccharide in good yield.



Scheme 2. Michael addition of a thiol-sugar.

Along with the progress in glycosidation chemistry, activation of the glycosyl donors by Lewis acids became an important method to synthesize thioglycosides with excellent stereoselective output. For example, a treatment of thiol with pentaacetyl glucose in the presence of boron trifluoride diethyl etherate affords the (1→1) linked thiodisaccharide in excellent yield and selectivity (Scheme 3).[20]

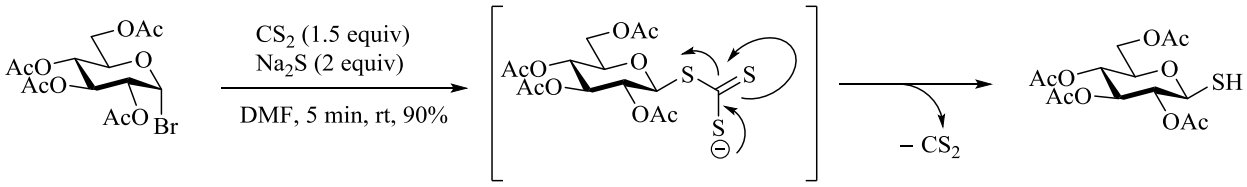


Scheme 3. Lewis acid promoted thioglycosidation.

The Schmidt group has introduced a novel approach for glycosidation by using *O*-Glycosyl trichloroacetimidates as glycosyl donors. Reaction of the thiol with imidate in the presence of promotor affords α selective (1→1) linked thiodisaccharide in good yield (Scheme 3).[21] In the stereocontrolled synthesis of glycosides various factors such as neighboring group participation, solvent and the promotor play a key role. Nonetheless, the corresponding sulfur monosaccharide analogs have to be prepared for the synthesis of thiodisaccharides; which will be briefly discussed in the following section.

Synthesis of the thiomonosaccharides

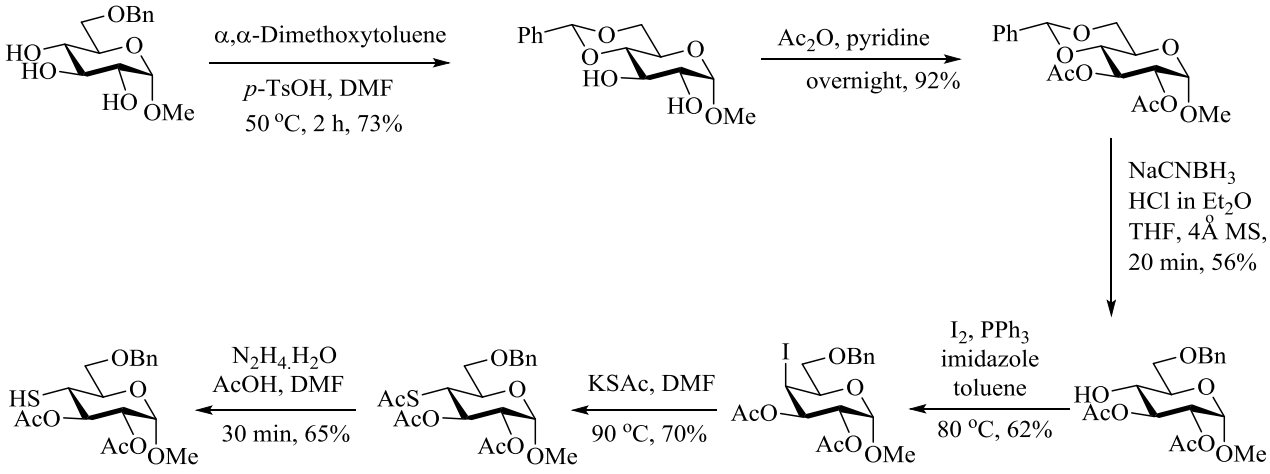
Although various strategies for the introduction of sulfur into carbohydrates exist in literature, many steps and low selectivities are disadvantageous. It is worth mentioning that introduction of the thiol group at the anomeric position can be easily accomplished by simple synthetic strategies. The classical approaches to prepare 1-thiosugars are based on nucleophilic substitution of the glycosyl acetates or halides with thiourea or thioacetate, within two steps.[22] In this particular insight, the Misra group has recently reported an efficient single step approach; which could be convenient to reduce the laborious efforts and time (Scheme 4).[23]



Scheme 4. Synthesis of a 1-thiosugar.

The *in situ* generated sodium carbonotrithiolate, obtained by the treatment of carbon disulfide (CS_2) with sodium sulfide ($Na_2S{\cdot}9H_2O$), reacts with acetobromo glucose to afford the 1-thiol in excellent yield and selectivity. Indeed, the stereochemical outcome in the synthesis of 1-thiol derived by the neighboring group participation of the acetyl group at the C-2 position.

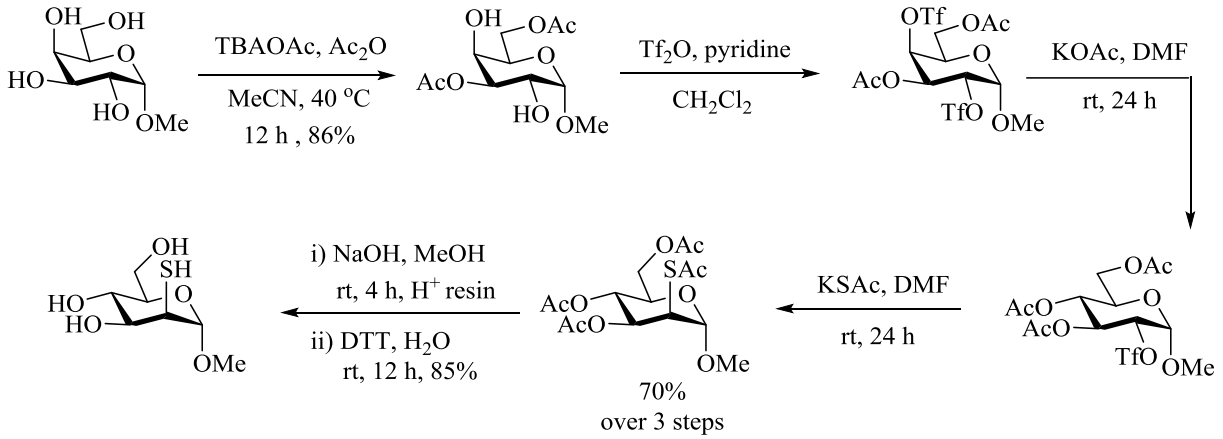
Contrary to this handy approach, introduction of the sulfur at other positions often requires lengthy synthetic transformations, including several protections and deprotections. For example, an excellent report by the Ramström group has revealed the synthesis of positional thiol analogs of galactopyranoside, including 2-thiols.[24]



Scheme 5. Synthesis of a 4-thiosugar.

Likewise, Ellis *et al.* reported a methodology to synthesize 4-thiols by a nucleophilic substitution of the corresponding iodide precursor with potassium thioacetate. A selective deprotection of the *S*-acetyl group affords the desired 4-thiol sugar (Scheme 5).[25]

Many steps are required while constructing the thiol functionality specifically at the C-2 position. Synthesis of the positional thiol analogs of mannopyranose was recently reported by the Dong group (Scheme 6).[26] Initially, the methyl galactopyranoside was converted into a suitable precursor for a nucleophilic substitution. In the next step, an S_N2 reaction of the triflate with potassium thioacetate followed by deacetylation under basic conditions affords a desired 2-thio mannopyranoside.



Scheme 6. Synthesis of a 2-thiosugar.

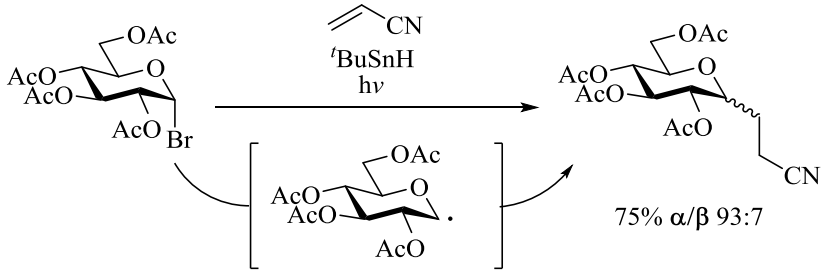
In spite of vigorous efforts that have been placed toward a synthesis of thiomonosaccharides, convenient and short routes are required to reduce the laborious work. Additionally, these described strategies are limited to the specific carbohydrates; therefore a general access which is applicable over the range of carbohydrates would enhance the synthetic value. The aim of this thesis was to develop a new entry to 2-thiosugars by a radical approach. Radical chemistry has become an important tool for the synthesis of functionalized carbohydrates, which will be described in the next section.

Radical reactions in carbohydrate chemistry

Over the past several decades, the progress of free-radical reactions has made remarkable changes in the area of chemical synthesis. Owing to their unique properties and distinction from other chemically reactive species, free radicals gained a vast consideration in various fields such as polymer chemistry, biology and organic synthesis.[27] Countless applications of radical reactions in organic synthesis have fascinated chemists to investigate their properties and proper mechanistic insights. In this perspective, particularly carbohydrates became attractive substrates

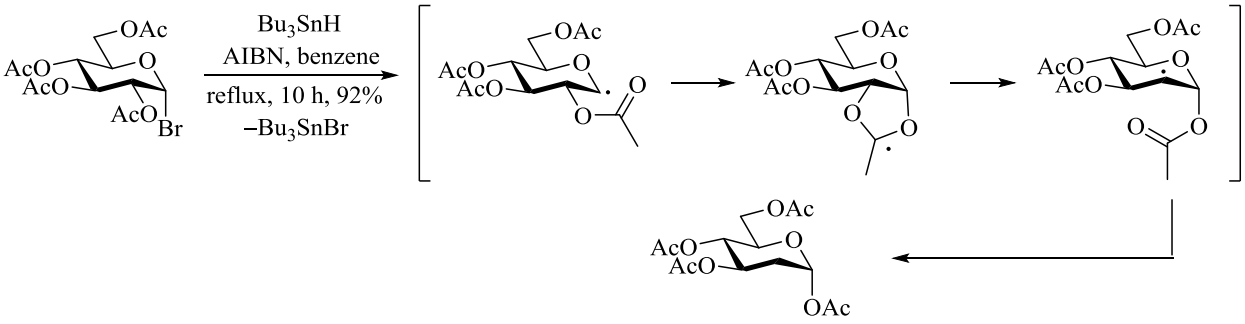
in the study of radical reactions concerning stereoselective synthesis of the biologically important molecules.[28]

The first application of radicals in carbohydrate chemistry has been described by Giese.[29] This pioneering work has opened a new area of research focusing the applications of radical chemistry in the synthesis of functionalized carbohydrates. For instance, the addition of pyranosyl radicals to activated olefins such as acrylonitrile or substituted acrylonitriles provides an access to the C–C bond formation reactions in carbohydrate chemistry.[30] The pyranosyl radical intermediate was generated photochemically by abstraction of a bromide atom from acetobromo glucose using tributyltin hydride. The resulting anomeric radical undergoes chain process with acrylonitrile to form a *C*-branched sugar in good yield and excellent selectivity (Scheme 7).



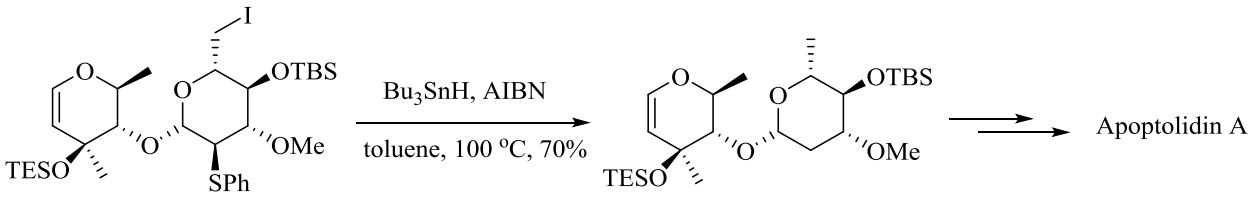
Scheme 7. The pyranosyl radical addition to acrylonitrile.

Based on the same approach, the synthesis of 2-deoxy sugars *via* an intramolecular acetoxy group rearrangement was demonstrated by Giese *et al*. In the absence of any additional acceptor, the anomeric radical undergoes a migration of the neighboring acetoxy group.



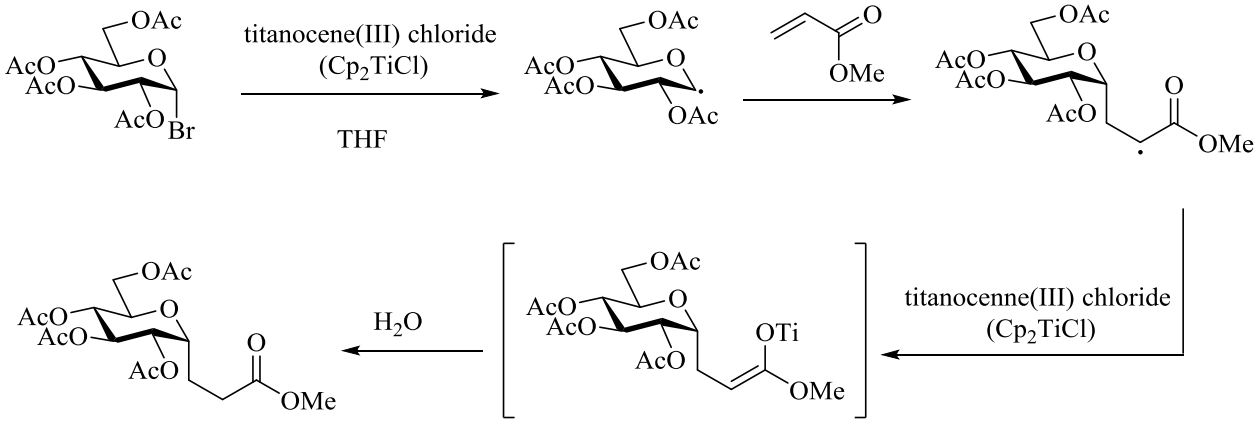
Scheme 8. Synthesis of a 2-deoxy sugar by radical rearrangement.

The hemiacetal radical rearranges to the 2-deoxy radical and finally abstracts a hydrogen atom to form the 2-deoxy sugar in excellent yield (Scheme 8). In the preparation of deoxy sugars, the desired functional group can be removed by a radical approach without affecting other groups. The Koert group has reported an efficient and single step reductive deiodination-desulfurization method by means of a radical activation.[31] In the total synthesis of sugar derived macrocycle apoptolidin A, 2-deoxy disaccharide building block was smoothly obtained from a corresponding iodo compound (Scheme 9).



Scheme 9. Synthesis of a 2-deoxy sugar building block.

The scope of radical mediated transformations of glycosyl halides is not just limited to the tinhydride chemistry; but can be extended to the synthesis of *C*-glycosides using transition metals. The Schwartz group has reported the trapping of the glucosyl radicals by acrylates to synthesize *C*-glycosides (Scheme 10).[32] In this particular reaction cascade, the mild and non-toxic reagent, titanocene(III) chloride was used instead of relatively toxic organotin compounds.

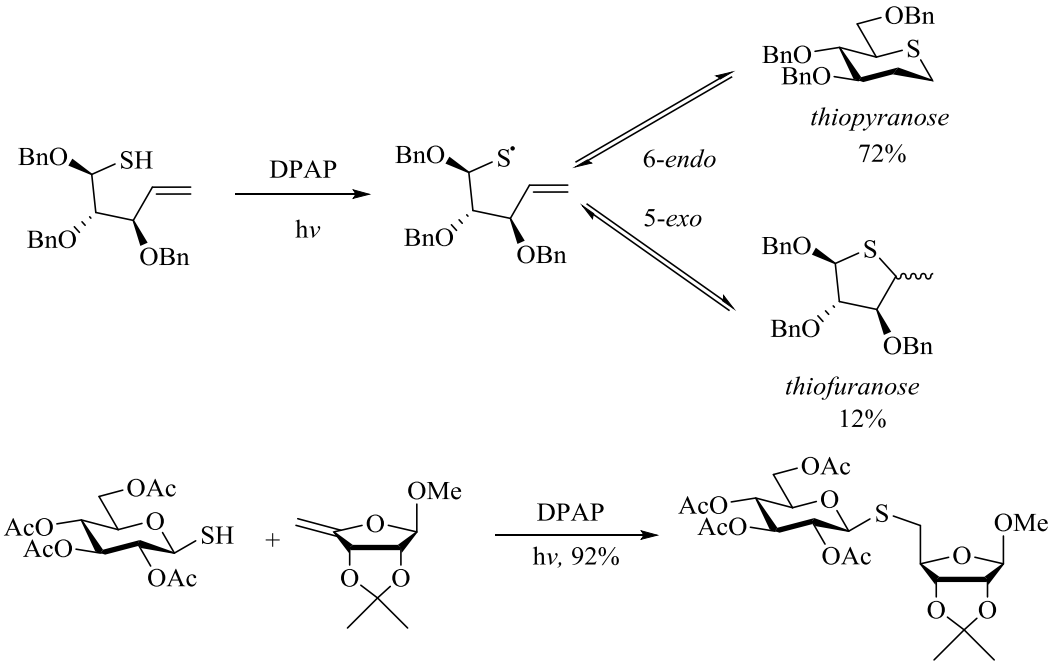


Scheme 10. Synthesis of a *C*-glycoside.

Generation of the anomeric radical was achieved by a reaction of acetobromo glucose with titanocene(III) chloride; which was trapped by methyl acrylate to generate α-carbonyl radical and undergoes further reaction with titanium reagent to furnish a desired *C*-glucoside. A comprehensive scope of the radical chemistry has been enriched with many new approaches. In this context, particularly thiyl radicals attracted a significant attention to synthesize thiosugars under mild reaction conditions.

Reactions of thiyl radicals in carbohydrate chemistry

Thiyl radicals have been extensively studied from various aspects including several biochemical processes, functionalization of the polymers and synthetic organic transformations. Addition of the thiyl radicals to olefins (thiol-ene coupling) became a popular strategy to synthesize a wide range of functionalized molecules containing thioether linkage.[33] Synthesis of the thiosugars can be achieved by addition of the thiyl radicals to suitable coupling partners under mild reaction conditions. Both intra- and intermolecular thiol-ene coupling are applicable to the synthesis and functionalization of the thiosugars as shown in the (Scheme 11).[34]

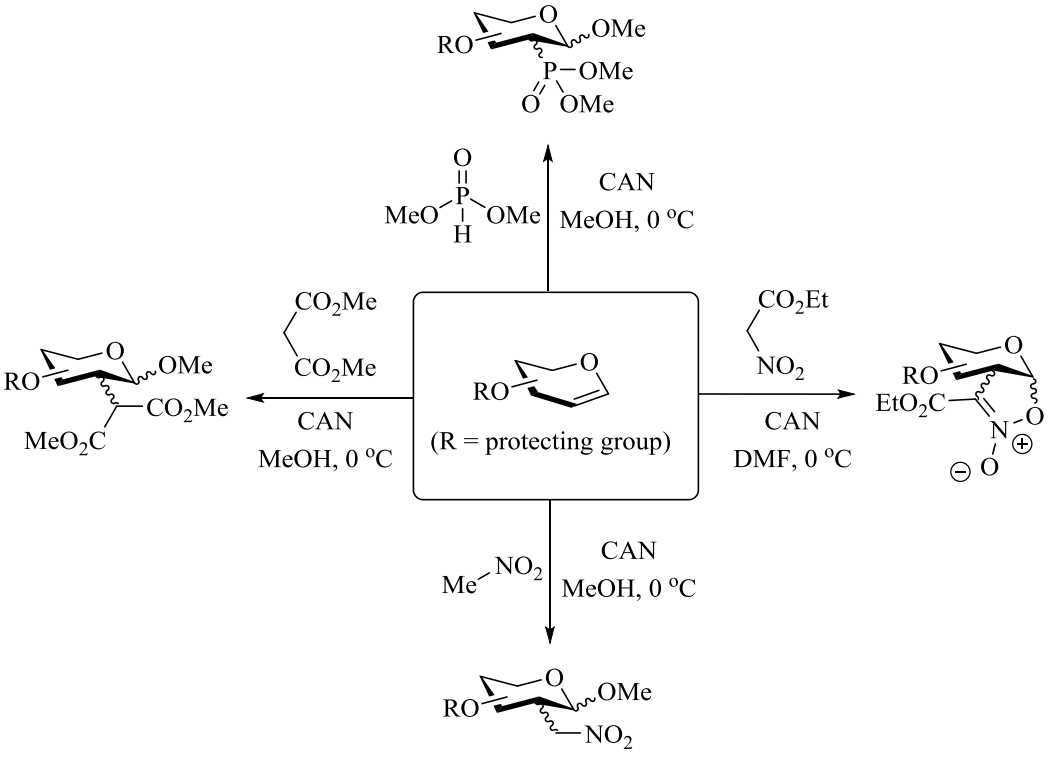


Scheme 11. Intra- and intermolecular thiol-ene coupling of thiosugars.

Intramolecular cyclization of a thiol under photochemical conditions provides cyclization products depending on the mode of addition. On the other hand, intermolecular addition of thiol to the sugar derived *exo*-alkenes affords a thiodisaccharide with excellent yield and distereoselectivity. More detailed investigations of thiol-ene coupling will be discussed in the following chapters.

Ceric ammonium nitrate mediated radical reactions in carbohydrate chemistry

Ceric ammonium nitrate (CAN) is a versatile reagent useful for the numerous applications in organic chemistry including oxidative addition, oxidation, nitration, photooxidation, deprotection, C-C bond formation and various multicomponent reactions.[35] Due to the strong redox potential (E° ~ 1.61 V vs. N.H.E.), CAN serves as a 'powerful one electron oxidant'; consequently, it attracts a significant attention toward the carbon-heteroatom bond forming reactions by a radical pathway.[36] In all described examples above, the carbohydrates served as radical precursors. A completely different approach with the carbohydrates as radical acceptor has been developed by the Linker group during the last years.[37]



Scheme 12. CAN mediated functionalization of the carbohydrates at the C-2 position.

The first example of CAN mediated radical addition to carbohydrates (glycals) was reported by Lemieux.[38] However, over a long time, scope of this methodology was limited to the azide radical addition, in order to synthesize 2-azido-carbohydrates. In this context, excellent work by the Linker group has extended the scope of this methodology, which in turn allows various transformations at the C-2 position and subsequent modifications at the anomeric center as well (Scheme 12).[39] CAN mediated radical additions of the CH-acidic compounds such as (dimethyl malonate, nitromethane and nitro esters) to glycals offer attractive precursors for further transformations.[40] A recent report also reveals the synthesis of sugar 2-phosphonates and subsequent applications in Horner-Emmons reaction.[41] In short, glycals have been employed for the construction of nitrogen, carbon and phosphorous linked non-reducing carbohydrates using ceric ammonium nitrate oxidations in methanol. Furthermore, the synthetic potential of this novel approach could also be explored to the sulfur linked carbohydrates. For this purpose, thiocyanate radicals became attractive substrates because they can be easily oxidized by CAN *via* single electron transfer (SET) and subsequently be transformed into thiols.

In this context, thiocyanate radicals have been successfully investigated for additions to the simple alkenes and arenes.[42] However, there is only one initial report from the Linker group on thiocyanate radical additions to glycals using SET.[43] This creates an opportunity to establish new synthetic entries to 2-thiocarbohydrates. A detailed study of the thiocyanate radical addition to glycals, the reaction mechanism, selectivity, chromatographic separation of stereoisomers formed and further transformations of the resulting thiosugars will be discussed in the following chapters.

3. Aim of the studies

Over the century, synthetically modified carbohydrates have gained a significant attention in the scientific community due to their interdisciplinary applications in fields including biology, polymer science, nutrition science and organic chemistry. In this context, replacement of the oxygen atom by other heteroatoms provides a huge library of sugar mimetics. Especially thiosugars are attractive carbohydrate mimetics from the biological perspective. Introduction of the sulfur in monosaccharides at the anomeric position could be achieved easily; however, it is challenging at other positions due to multistep synthesis and low stereoselectivities. With this idea, we were fascinated to investigate the synthesis of thiosugars by convenient approaches, focusing the C-2 position (Figure I).

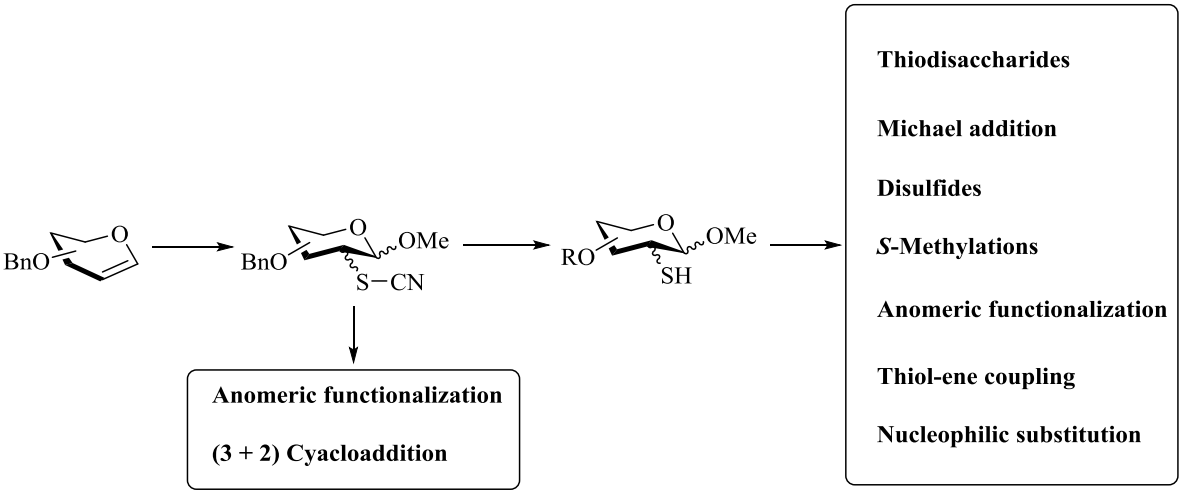


Figure I. Aim of the studies.

- To develop a facile entry to 2-thiocyanates by a radical approach
- To synthesize 2-thiols and disulfides
- To synthesize 2-*S* linked thiodisaccharides by thiol-ene coupling and nucleophilic substitution
- To functionalize the 2-thiosugars at the anomeric position by Lewis acid catalysis
- To investigate the scope and limitations of these approaches

4. Results and discussion

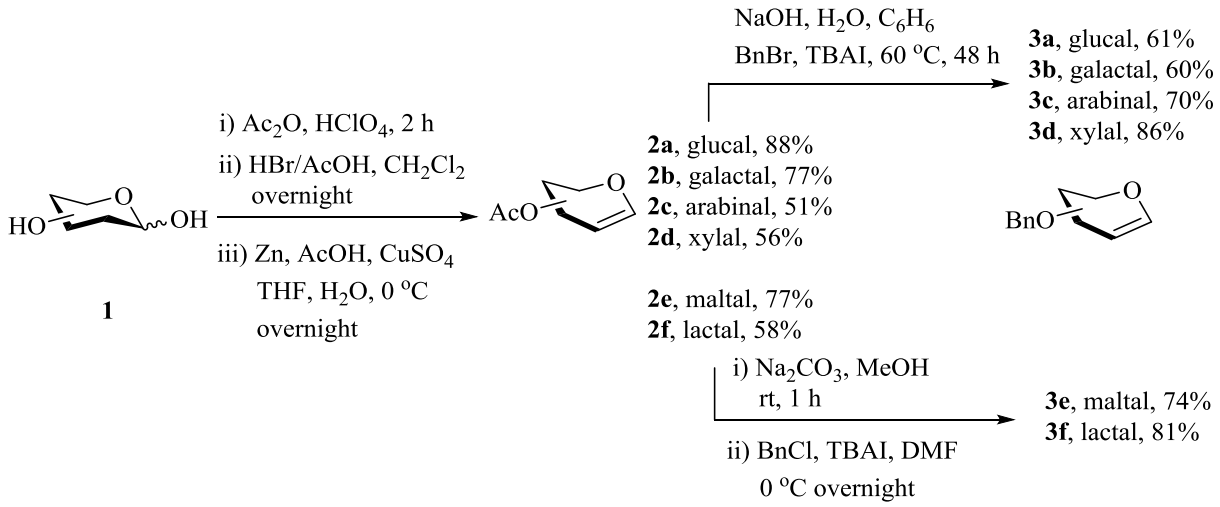
(Chapter 1)

Ceric ammonium nitrate (CAN) mediated thiocyanate radical additions to glycals

In this chapter, a convenient synthesis of 2-thiocyanato carbohydrates *via* radical addition of ammonium thiocyanate to benzyl protected glycals followed by their transformations to free thiols will be discussed. Ceric ammonium nitrate (CAN) functions as an excellent oxidant for the generation of thiocyanate radicals in methanol.[44] Specifically, CAN medicated radical additions to glycals proceed by excellent regioselectivity of the addition products. Indeed, a remarkable stability of the glycals in CAN mediated reactions proving them as valuable building blocks in carbohydrate chemistry.[45]

4.1.1. Synthesis of glycals

Glycals are 1,2 unsaturated carbohydrate derivatives, which contain an *endo*-cyclic double bond or more precisely a 'cyclic enol-ether' in their core structure. Starting materials used during the entire studies were synthesized according to the well-established literature procedures and protocols modified in the laboratory.[46] In order to compare the impact of configuration and orientation of the protecting groups on radical additions, six different glycals were chosen; including hexoses (glucal, galactal), pentoses (xylal, arabinal) and disaccharides (lactal, maltal). Reactivity of the radical additions to the glycals is influenced by the nature of protecting groups. This can be easily elucidated by the impact of electron donating and withdrawing protecting groups on electron density at the double bond. Thus, acetyl and benzyl protected glycals were considered as attractive precursors for the envisioned synthesis of 2-thiocarbohydrates. Shown in the Scheme 4.1.1, synthesis of the glycals was achieved by simple synthetic transformations. For example, a global acetylation of the glucose followed by a treatment with hydrogen bromide affords acetobromo glucose. In the subsequent step, reductive elimination by zinc in the presence of catalytic amounts of copper sulfate affords acetyl protected glucal in excellent yield. This protocol was successfully applied for the chosen set of carbohydrates to obtain acetyl protected glycals (**2a**–**2f**) in analytically pure form.



Scheme 4.1.1. Synthesis of acetyl- and benzyl-protected sugars.

On the other hand, moderately electron rich benzyl protected glycals (**3a**–**3f**) were obtained from corresponding acetyl protected glycals by the deprotection-protection sequence. Interestingly, both, acetyl and benzyl protected glycals are suitable for the radical additions; however, they are highly selective for specific radicals. For instance, CAN mediated radical additions of dimethyl phosphite and nitromethane were effective only in the case of benzyl protected glycals, whereas addition of the dimethyl malonate was successful with acetyl protected glycals as well.[37,40,41]

4.1.2. Screening of the substrates for radical additions to glycals

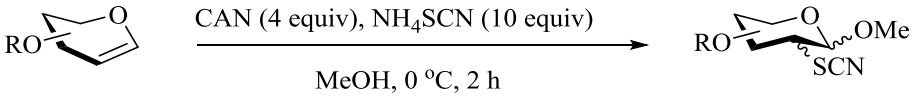
In order to establish an access to 2-thiocarbohydrates, glycals were subjected to various reaction conditions. In this context, preliminary observations by Dr. Elangovan Elamparuthi were extremely helpful to follow the studies.[43] In the initial attempts, acetyl protected glycals were considered for the optimization studies. However, a reaction between acetyl protected glucal **2a** and ammonium thiocyanate in the presence of CAN was unsuccessful. Even high concentrations of the reactants couldn't give an access to the addition products. It was postulated that the low electron density at the double bond of glucal, derived by the electron withdrawing acetyl groups impairs the addition of thiocyanate radicals to the glycals. Alternatively, potassium thiocyanate (KSCN) and other oxidizing agents such as $Mn(OAc)_3$, $K_2S_2O_8$ and $(NH_4)_2S_2O_8$ were investigated; however, these reaction conditions were also unproductive. Thus, in the next approach, moderately electron rich glycals bearing benzyl groups were explored. Interestingly,

addition of ammonium thiocyanate to the benzyl protected glycals in the presence of CAN took place smoothly. Indeed, this improved reactivity could be a product of the enhanced electron density at the double bond; thus benzyl protected glycals were utilized for further optimization of the reaction conditions. It was observed that the dropwise addition of CAN to a solution of glucal and ammonium thiocyanate in methanol lead to many products; which were detected by the TLC and NMR analyses. Finally, in a slightly modified approach, CAN and NH_4SCN were added to the glucal in simultaneous manner. Applied with the adapted reaction conditions, a significant improvement was observed by complete conversion of the starting materials. It would also be important to take into account that the excess of reagents are required for a smooth generation of thiocyanate radicals; since a simultaneous oxidation could suppress their availability by forming the dithiocyanate dimers. Consequently, the presence of the thiocyanate group was confirmed by signals at the anomeric and nitrile regions in ^{13}C NMR spectra, which will be discussed in the next section.

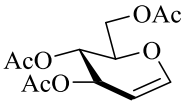
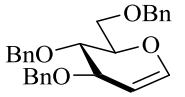
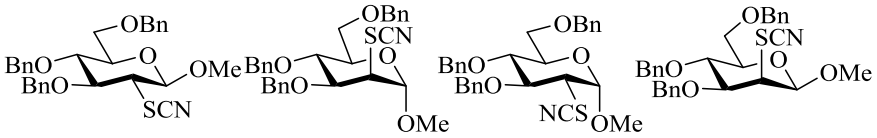
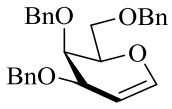
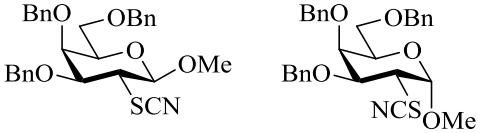
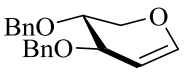
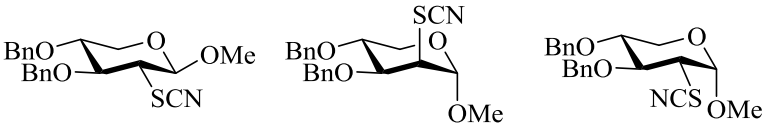
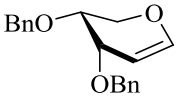
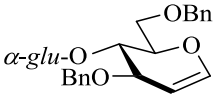
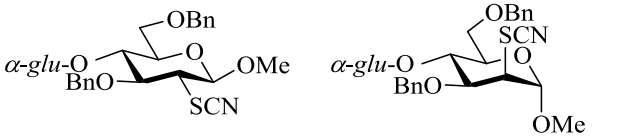
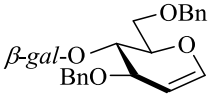
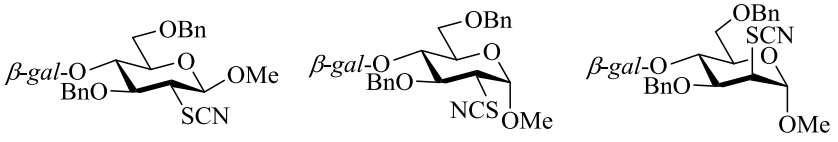
4.1.3. Thiocyanate radical addition to glycals

To extend the scope of methodology, optimized reaction conditions were applied to the various glycals for the synthesis of 2-thiocyanato carbohydrates. Since acetyl protected glycals were not suitable for the synthesis of 2-thiocyanates, rest of the studies were conducted with benzyl protected glycals (entry 1, Table 4.1.1). The stereochemical outcome in these reactions is dependent on the stability of newly formed carbon centered radical intermediates and subsequent oxocarbenium ions. Four addition products are expected due to the formation of two new stereocenters. Nonetheless, the usual trend in the selectivities was found remarkably consistent by a predominant formation of one of the most favorable 2-thiocyanate products. Indeed, these selectivities are by virtue of the orbital interactions established by the protecting groups. For instance, a *trans*-relationship was observed in all major addition products between the 3-*O*-benzyl and thiocyanate group present at the C-3 and C-2 positions, respectively (entries 2–7). Furthermore, orientation of the methoxy group at the anomeric position was found specifically *anti* to the thiocyanate groups in most of the major addition products; however, galactal and arabinal follow the opposite selectivity (entries 3 and 5). Finally, formation of the addition products was confirmed by the crude NMR analysis and subsequently isolated in analytically pure form by silica gel column chromatography.

Table 4.1.1. Radical addition of ammonium thiocyanate to glycals.

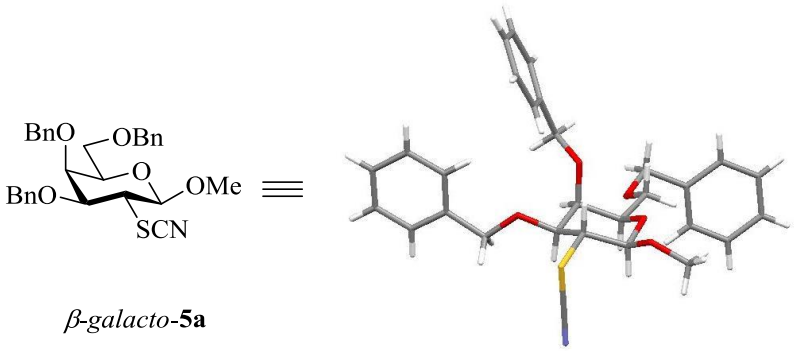


glycals **(2a–3f)** — 2-thiocyanates **(4a–9c)**

Entry	Glycals	2-thiocyanates[a]
1	 *glucal*-**2a**	No conversion
2	 *glucal*-**3a**	 *β-gluco*-**4a** (44%) *α-manno*-**4b** (20%) *α-gluco*-**4c** (7%) *β-manno*-**4d** (3%)
3	 *galactal*-**3b**	 *β-galacto*-**5a** (14%) *α-galacto*-**5b** (53%)
4	 *xylal*-**3c**	 *β-xylo*-**6a** (63%) *α-lyxo*-**6b** (16%) *α-xylo*-**6c** (3%)
5	 *arabinal*-**3d**	 *β-arabino*-**7a** (72%) *α-arabino*-**7b** (21%)
6	 *maltal*-**3e**	 *β-malto*-**8a** (45%) *α-epi-malto*-**8b** (17%)
7	 *lactal*-**3f**	 *β-lacto*-**9a** (50%) *α-lacto*-**9b** (8%) *α-epi-lacto*-**9c** (16%)

[a]Yield of analytically pure products, isolated by column chromatography.

Furthermore, a typical shift around 100 ppm confirms the presence of the methoxy group at the anomeric position in corresponding 2-thiocyanates. Also, large couplings around 8.5 Hz were observed for the 1,2-*trans* sugars; whereas small couplings around 3.5 Hz were characteristic to the *cis* compounds. More detailed and specific structural assignments were performed using 2D experiments. For example, the heteronuclear correlations between the carbon and attached hydrogen were confirmed by the HMQC or HSQC techniques. Nonetheless, it was challenging to assign the orientation of the methoxy groups at the anomeric position merely on the basis of coupling constants between the anomeric and H-2 protons. Thus, 'coupled HSQC' experiments were carried out to differentiate the characteristic C-H coupling constants for α or β methyl-anomers.[47] For example, α methoxy groups present at the anomeric position show a large coupling constant around 170 Hz; while, a slightly lower coupling constant around 160 Hz was observed for β methoxy groups. Thus, the corresponding α or β methyl-anomers were unambiguously determined by this technique. Finally, a single crystal X-ray structure of *β-galacto*-**5a** also provides a concrete evidence for the formation of 2-thiocyanates (Figure 4.2.1)



β-galacto-**5a**

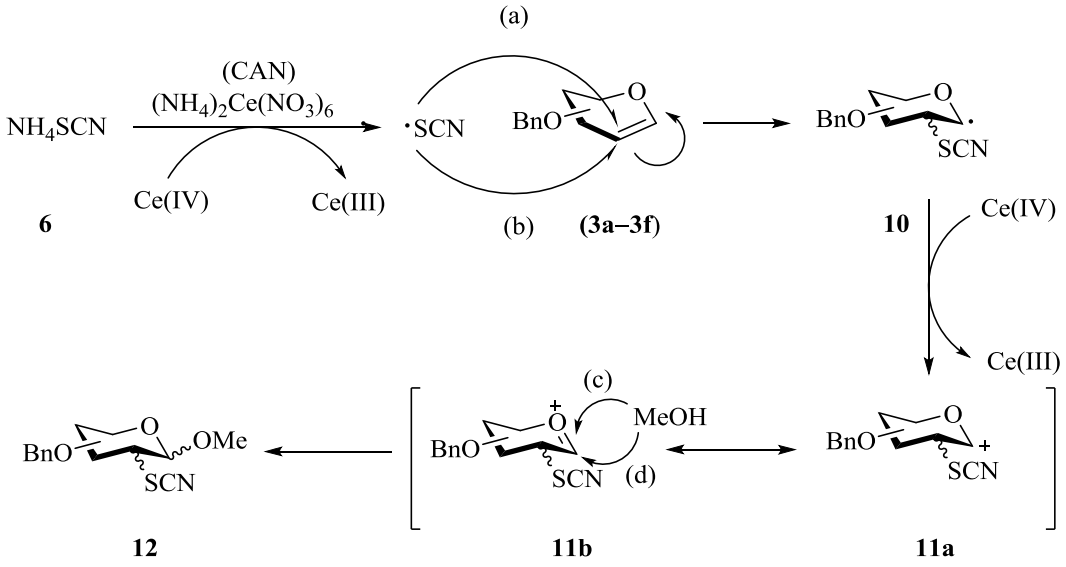
Figure 4.2.1. Single crystal X-ray structure of *β-galacto*-**5a**.

Most of the 2-thiocyanates were isolated as viscous liquids; nevertheless, only *β-galacto*-**5a** was successful to achieve the single crystal growth under appropriate solvent. Formation of the stereoisomers and the detailed reaction mechanism will be discussed in the following section.

4.1.4. Reaction mechanism

The proposed reaction mechanism for the thiocyanation of carbohydrates proceeds as shown in Scheme 4.1.2. Formation of a new C-S bond takes place by the addition of thiocyanate radicals

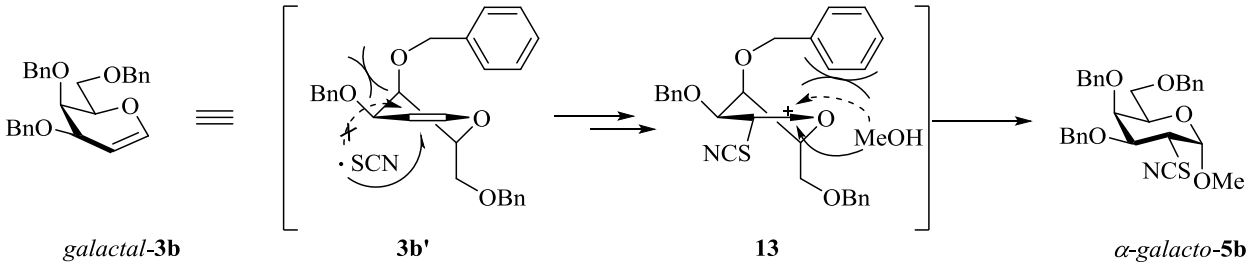
to glycals. A treatment of ammonium thiocyanate **6** with CAN in methanol generates thiocyanate radicals, which undergo further addition to glycals, selectively at the C-2 position to form a new radical **10** at the anomeric position. Selectivity in the addition process is due to the stabilization of the anomeric radical by the adjacent ring oxygen. This regioselective addition could occur from either the upper (a) or lower (b) face, but the latter is preferred due to the orbital control derived by a protecting group at the C-3 position. Thus, all major addition products follow the same selectivity pattern, where the thiocyanate group is *anti* to the 3-*O*-benzyl group.



Scheme 4.1.2. Proposed mechanism for the thiocyanate radical addition to glycals.

Next, the anomeric radical **10** is further oxidized by CAN to generate a stable carbocation **11a**; which can be trapped by methanol from either the equatorial (c) or axial (d) site to form *α/β* mixtures of methyl glycosides. Contrary to the addition of malonates to glycals, an anomeric carbocation cannot be stabilized by neighboring group participation of the electron withdrawing thiocyanate group; thus, four possible isomers of **12** can be formed during the addition. Interestingly, in the case of *galactal*-**3b**, the oxocarbenium ion is trapped by methanol from the lower site to furnish *α*-methyl 2-thiocyanate as a major product. The only highlighting difference between glucal and galactal at the C-4 position alters the reactivity pattern. Corresponding selectivity could be justified on the basis of a shielding effect induced by an axial *O*-benzyl group at the C-4 position of the benzyl protected galactal.[48] As shown in the Scheme 4.1.3, this effect can be easily described with a half chair conformation of the *galactal*-**3b'**; thus, attack of

the thiocyanate radical and later trapping of the oxocarbenium ion by methanol takes place from the lower site.



Scheme 4.1.3. Proposed mechanism for the formation of *α-galacto*-**5b**.

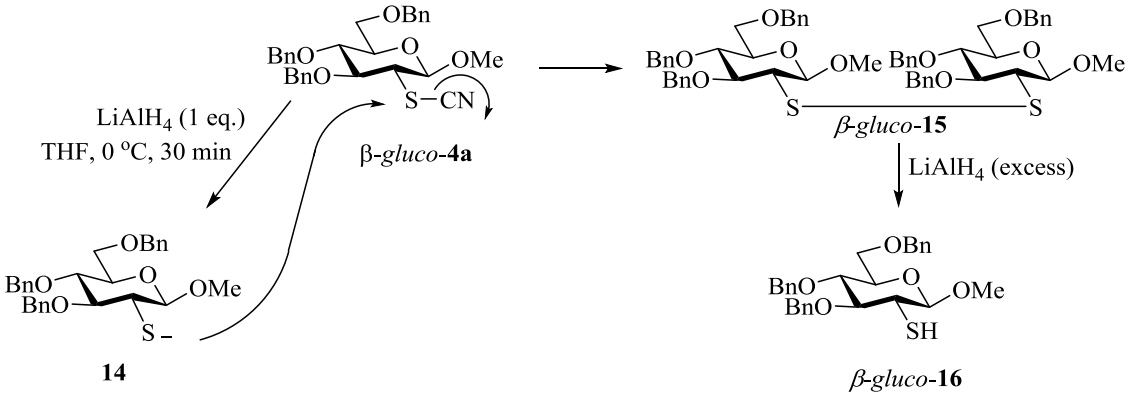
In the case of arabinal, the major addition product undergoes ring flipping to acquire the more favorable conformation; which is in agreement with the addition of malonates and phosphonates to the arabinal.[37,41] The overall process of the formation of 2-thiocyanates is mechanistically triggered by the favorable orbital interactions between the SOMO of the thiocyanate radical and HOMO of the double bond in glycals.[45] In the subsequent part of studies, all major addition products were transformed to thiols by means of appropriate reduction methods; which will be discussed in the following section.

4.1.5. Reductions of the 2-thiocyanates to thiols

Thiocyanates are attractive precursors for the construction of a thiol group over a wide range of organic molecules due to the good leaving group ability of the nitrile group.[49] Thus, thiocyanates become useful as a mild and electrophilic sulfur transfer reagents for the synthesis of thiols, thioethers and disulfides. The main objective of the following studies was to reduce both the nitrile and benzyl groups in the same step to obtain globally deprotected 2-thiols; which are analogous to naturally occurring methyl glycosides.

As a first approach, several palladium based catalysts were screened for the catalytic hydrogenation; however, due to the catalyst poisoning induced by sulfur, no conversion was observed.[50] In the alternative approach, thiocyanates were first reduced to thiols using lithium aluminium hydride ($LiAlH_4$).[51] Interestingly, 1 equivalent of $LiAlH_4$ afforded disulfide **15** in 77% yield as a major product along with 13% of the thiol. We rationalized that an air oxidation

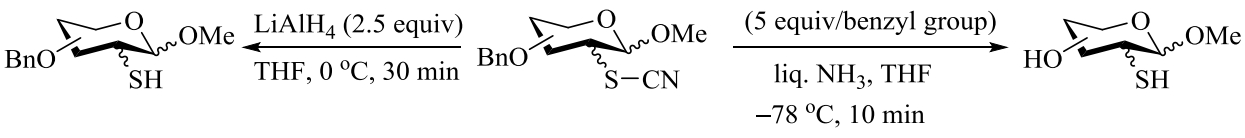
of the thiol could bring about a dimerization; however, formation of the disulfide couldn't be suppressed under strict anaerobic conditions as well. It was postulated that the reaction between *in situ* generated thiolate intermediate **14** with unreacted thiocyanate lead to the formation of disulfide *via* nucleophilic substation (S_N2). This hypothesis was further validated by an independently performed control experiment, where thiolate was treated with the 2-thiocyanate **4a** to obtain an identical disulfide **15** in 76% yield. Finally, excess of the $LiAlH_4$ was used to accomplish a complete conversion of thiocyanate to thiol *via* further reduction of the disulfide intermediate; which could be easily monitored by TLC (Scheme 4.1.4). Important caution has to be taken due to the liberation of highly toxic hydrogen cyanide during the $LiAlH_4$ reductions. Thus, all reactions and workup were performed under careful handling in a fume hood.



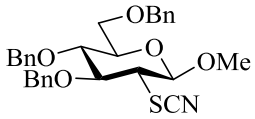
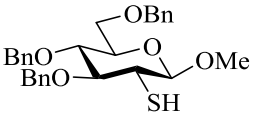
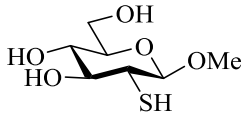
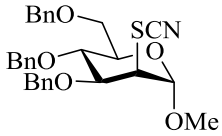
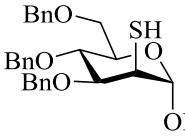
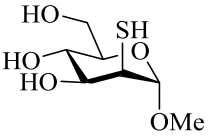
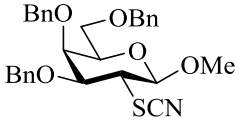
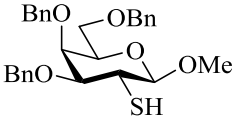
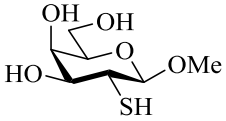
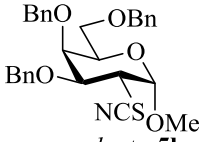
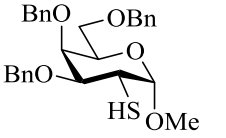
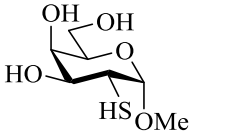
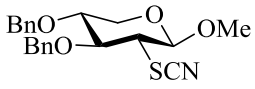
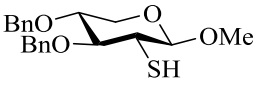
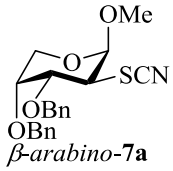
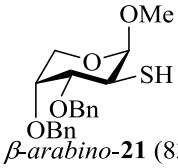
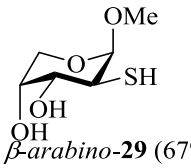
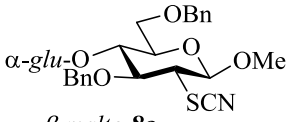
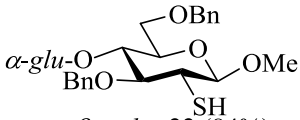
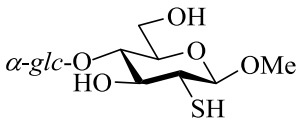
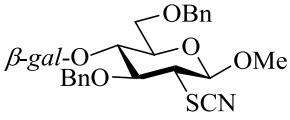
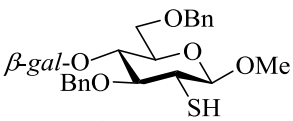
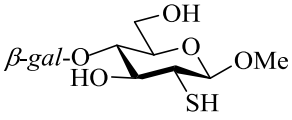
Scheme 4.1.4. Proposed mechanism for the reduction of thiocyanate **4a** to thiol **16**.

In the next approach, 2-thiols were subjected to catalytic hydrogenation; however the desired debenzylation was predictably unsuccessful. Therefore, it was necessary to explore other methods to obtain an access to protecting group free thiols. Finally, we switched to the Birch reduction; which is quite well-known protocol for debenzylation of the sulfur containing compounds.[52] Consequently, *gluco*-**4a** was treated with a reducing mixture obtained from the dissolved sodium in liquid ammonia. Indeed, under such reducing conditions, both nitrile and benzyl groups were successfully cleaved in a single step to furnish a protecting group free thiol **24**. For purification, a treatment of H^+ ion exchange resin is applicable to replace the Na^+ ions from the reaction mixture. However, due to the sensitivity of free thiols towards oxidation to disulfides, ammonium chloride was used to exchange the sodium ions followed by a quick filtration-cum-purification through a silica gel.

Table 4.1.2. Synthesis of the 2-thiols.



16–23 *(method A)* **4a–9a** *(method B)* **24–31**

Entry	Thiocyanate	Method A Product[a]	Method B Product[a]
1	 *β-gluco*-**4a**	 *β-gluco*-**16** (83%)	 *β-gluco*-**24** (78%)
2	 *α-manno*-**4b**	 *α-manno*-**17** (85%)	 *α-manno*-**25** (75%)[b]
3	 *β-galacto*-**5a**	 *β-galacto*-**18** (86%)	 *β-galacto*-**26** (65%)
4	 *α-galacto*-**5b**	 *α-galacto*-**19** (86%)	 *α-galacto*-**27** (71%)
5	 *β-xylo*-**6a**	 *β-xylo*-**20** (82%)	 *β-xylo*-**28** (69%)[b]
6	 *β-arabino*-**7a**	 *β-arabino*-**21** (83%)	 *β-arabino*-**29** (67%)[b]
7	 *β-malto*-**8a**	 *β-malto*-**22** (84%)	 *β-malto*-**30** (68%)
8	 *β-lacto*-**9a**	 *β-lacto*-**23** (93%)	 *β-lacto*-**31** (70%)

[a]Yield of analytically pure products, isolated by column chromatography.

[b]Sensitive to the air oxidation.

A parallel protocol could also be applied involving a Birch reduction followed by acetylation and then deprotection of acetyl groups under basic conditions to obtain the free thiols. From a mechanistic point of view, cleavage of each benzyl group requires two equivalents of sodium to bring about two sequential single electron transfer processes. However, as compared to the stoichiometric amounts, excess of sodium resulted in better yields by readily available electrons for the reduction. Finally, to explore the substrate scope of these methods, 2-thiocyanates were reduced to thiols as shown in the Table 4.1.2. Both reduction methods were applicable over a range of 2-thiocyanates (**4a**–**9a**) by providing analytically pure 2-thiols (**16**–**31**) in good to excellent yields (entries 1–7). It should be mentioned that handling of the crude reaction material and purified compounds has to be done carefully due to the sensitivity of thiols towards air oxidation.

Finally, a graphical interpretation depicts the comparison between the representative thiocyanate, disulfide and thiols by characteristic signals appeared in a combined APT NMR spectrum, as shown in the Figure 4.1.2.

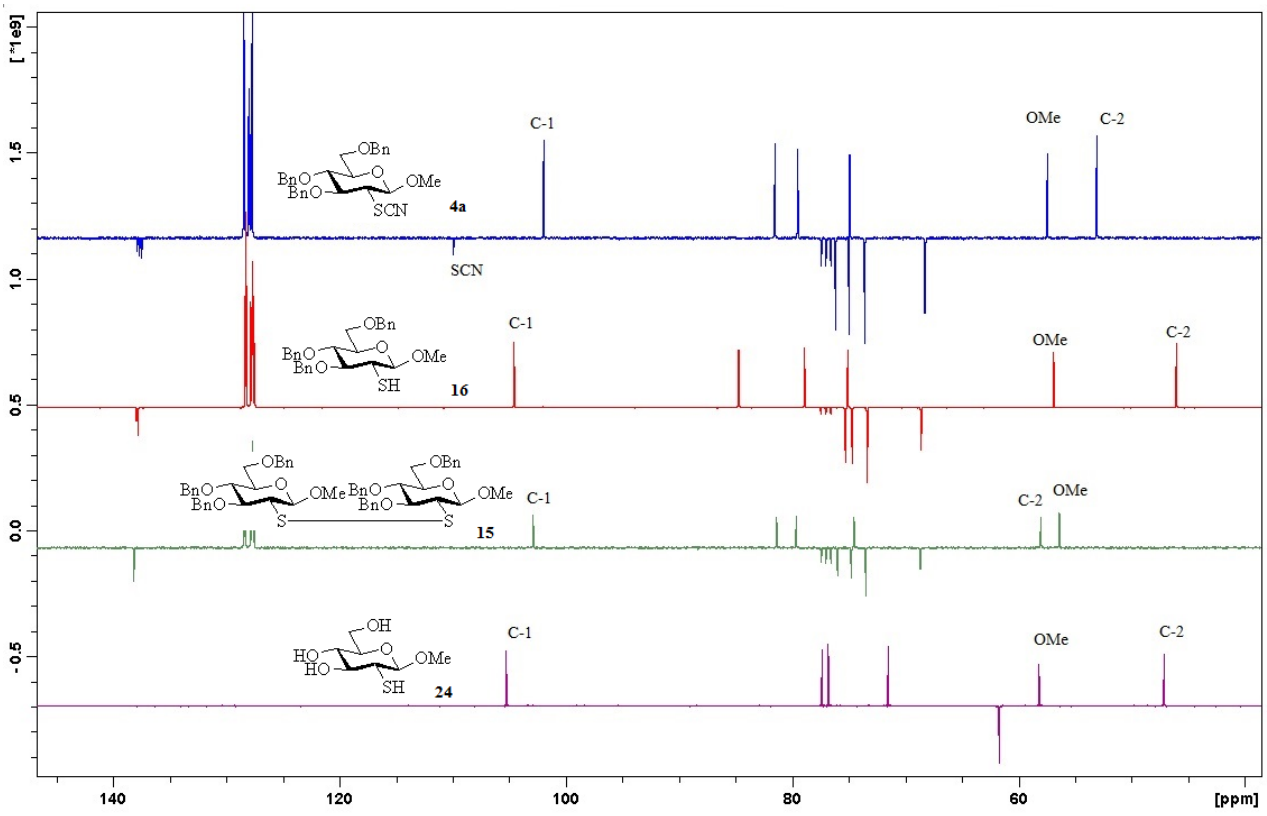


Figure 4.1.2. Combined APT spectra of the 2-thiocyanate **4a**, disulfide **15** and thiols **16** & **24**.

Thiocyanates and thiols can be distinguished by a disappearance of the nitrile group in the ^{13}C NMR spectra, whereas a high-filed shift for the C-2 carbon confirms the formation of disulfide. Interestingly, the H-2 proton belonging to the protected thiol splits with a (ddd) pattern due to the additional coupling from the thiyl group, while thiocyanates and free thiols show a (dd) pattern in the proton NMR spectra. Contrary to the protected thiols, due to the presence of exchangeable protons, the thiyl group was undetectable in the case of free thiols. Finally, 2-thiols were fully characterized by advanced analytical methods and further utilized for the synthesis of thiodisaccharides and various transformations. These results were successfully published by our group by providing a new entry for the synthesis of 2-thiocarbohydrates.[53]

4.1.6. Summary

In summary of this chapter, a new methodology to synthesize 2-thiocarbohydrates from glycals was disclosed. As compared to the classical methods known in the literature for introduction of sulfur at the C-2 position, this convenient approach provides a quick two-step access to obtain free thiols from commercially available starting materials. Also, most of the known methodologies are specific to the synthesis of a particular 2-thiol; however this approach is applicable to all glycals (including hexoses, pentoses and disaccharides), presenting its generality from a broader perspective. Moreover, standard reaction conditions for the CAN mediated radical additions to the glycals were successfully applied to synthesize 2-thiocyanates. More detailed insight in the stereochemical outcome and the reaction mechanism has been discussed to propose the formation of the C-S bond. Interestingly, high regioselectivity and predominant formation of one of the addition products enhances the overall utility of the methodology on a preparative scale. In the second part of studies, flexibility in the transformations of 2-thiocyanates to 2-thiols has been achieved by choosing an appropriate reduction method. In addition, an interesting mechanism for the formation of disulfide *via* nucleophilic substitution has been proposed and subsequently confirmed by a control experiment. Thus, new building blocks for the sulfur containing carbohydrates are easily available by a transition metal mediated thiocyanate radical additions to glycals. Various transformations of 2-thiols concerning the synthesis of thiodisaccharides and carbohydrate linked sulfides will be discussed in the next chapters.

(Chapter 2)

Synthetic transformations of the 2-thiocarbohydrates

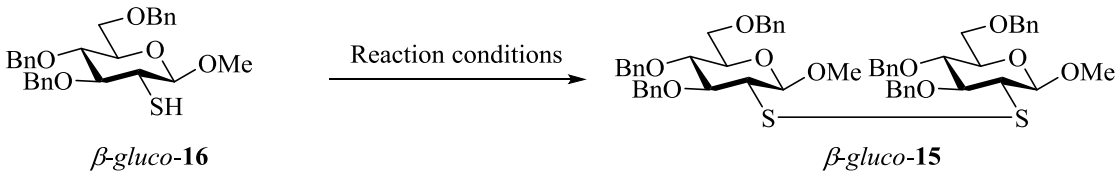
In this chapter simple synthetic transformations of 2-thiosugars will be discussed. Synthesis of thiol monosaccharides and thiodisaccharides attract a significant attention concerning studies of enzymatic processes.[54] Numerous approaches to construct a sulfur linkage between two carbohydrates at the anomeric position are well documented and further investigated for the enzymatic studies. In this context, 2-thiols are suitable precursors to synthesize 2-*S* linked thiodisaccharides and would also be potential targets for the biological screening. In the following studies, phase transfer catalyst (nucleophilic) and thiol-ene coupling (radical) based syntheses of thiodisaccharides are the highlighted approaches. This section will cover the transformations of 2-thiols by a nucleophilic pathway (*S*-alkylations), oxidation to disulfides and Lewis acid mediated functionalization at the anomeric position. Additionally, synthesis of a 2-*S* linked heterocycle by (3 + 2) cycloaddition between azide and a 2-thiocyanate, trapping of the anomeric position by water and further modifications will be described.

4.2.1. Synthesis of disulfides

In order to explore the functionalization of 2-thiols, we were interested in oxidations of thiols to disulfides by a convenient method. To the best of our knowledge, only few examples of sugar disulfides at the C-2 position are known in the literature. However, these examples are based on *in situ* dimerization of *S*-benzyl sugars under highly drastic conditions using highly toxic mercury reagents and are not fully characterized.[55] As aforementioned, the reduction of 2-thiocyanates with one equivalent of lithium aluminium hydride resulted in a mixture of thiol and disulfide. Despite a predominant formation of the disulfide, a selective control couldn't be achieved over the subsequent reduction to thiols. In the alternative strategy, we sought for oxidizing agents to synthesize (2→2) linked sugar disulfides starting from the 2-thiols. Even though thiols can be converted to disulfides by air oxidation, the overall process is rather sluggish. Therefore, in order to optimize suitable reaction conditions for the disulfide formation, thiol *β-gluco*-**16** was chosen as a model sugar (Table 4.2.1). As compared to thiols, thiolates are more prone to the oxidation under aerobic conditions. During the course of studies, it was observed that tetra-*n*-butyl ammonium fluoride (TBAF) facilitates the conversion of 2-thiol to

disulfide **15** smoothly under aerobic conditions; however, scale up resulted in a lower yield (entries 1 and 2).

Table 4.2.1. Optimized synthesis of a disulfide **15**.



β-gluco-**16** *β-gluco*-**15**

Entry	Reaction conditions	Time	Yield (%)[a]
1	TBAF, THF, rt	10 min	98
2	TBAF, THF, rt	60 min	71[b]
3	TBAB, THF, rt	–	no conversion
4	TBAI, THF, rt	–	no conversion
5	DDQ, DCM, rt	30 min	86
6	I_2, pyridine, rt	15 min	92

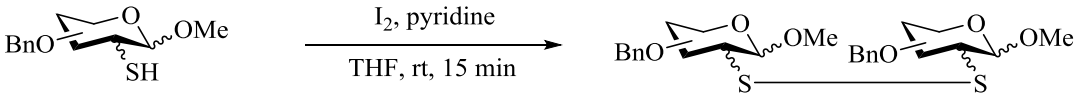
[a] Yield of analytically pure products, isolated by column chromatography.

[b] Scale up resulted in reduced yield.

Surprisingly, in contrast to TBAF, other tetra-*n*-butyl ammonium halides were unable to achieve the desired conversion (entries 3 and 4). A plausible mechanism could be anticipated on the basis of deprotonation of the thiol group followed by a quick air oxidation to the disulfide. However, no literature evidence is available to support the dimerization of the thiol by this method. Subsequently, we screened other oxidizing agents such as 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) and iodine. A recent report by Smith and co-workers reveals the synthesis of α,α-linked symmetric as well as asymmetric sugar disulfides using these reagents.[56] Thus, similar reaction conditions were applied for the synthesis of (2→2) linked symmetric disulfides. Though, both oxidizing agents are suitable, the iodine method was preferred due to the improved yield and low toxicity as compared to the DDQ (entries 5 and 6). Mechanistically, oxidation of the thiol took place smoothly in the presence of pyridine *via* a thiolate intermediate. On the other hand, oxidizing agents such as hydrogen peroxide (H_2O_2) or *meta*-chloroperbenzoic acid (mCPBA) haven't been examined, due to the possibility of over oxidation to sulfones and

sulfoxides.[57] Finally, to explore the scope of the methodology, various sugar thiols were investigated under optimized reaction conditions as shown in the Table 4.2.2. All thiols were successfully oxidized to the disulfides and purified by silica gel column chromatography in excellent yields (entries 1–7).

Table 4.2.2. Synthesis of the symmetric disulfides.

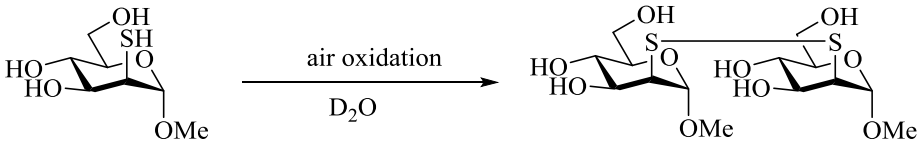


16, 18–23 **15, 32–37**

Entry	Thiol	Disulfide	Yield(%)[a]
1	*β-gluco*-**16**	*β-gluco*-**15**	92
2	*β-galacto*-**18**	*β-galacto*-**32**	90
3	*α-galacto*-**19**	*α-galacto*-**33**	93
4	*β-xylo*-**20**	*β-xylo*-**34**	87
5	*β-arabino*-**21**	*β-arabino*-**35**	90
6	*β-malto*-**22**	*β-malto*-**36**	86
7	*β-lacto*-**23**	*β-lacto*-**37**	89

[a] Yield of analytically pure products, isolated by column chromatography.

As compared to any other oxidizing agents, air serves as a cheapest oxidant for the conversion of thiols to disulfides; however, the rate of the oxidation depends on reactivity and availability of molecular oxygen during the process.



α-manno-**25** *α-manno*-**38**
(complete conversion)

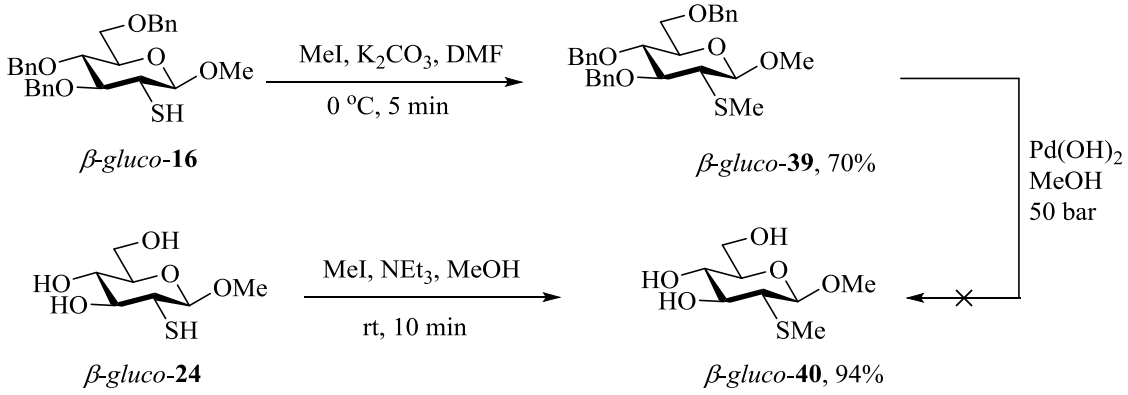
Scheme 4.2.1. Air oxidation of thiol *α-manno*-**25**.

For instance, an excellent solubility of protecting group free 2-thiols in water facilitates the spontaneous oxidation under mild reaction conditions. As shown in Scheme 4.2.1, overnight exposure of the *manno*-thiol **25** to air furnishes the corresponding dimer **38** with complete conversion, which was monitored by NMR spectroscopy. Formation of the disulfide was confirmed by characteristic high-filed shifts for the anomeric proton and the C-2 carbon. Nevertheless, it was observed that the reactivity of free thiols towards air oxidation is influenced by the steric factors. The sterically less crowded *manno*-thiol undergoes faster dimerization as compared to the *gluco*-thiol. Therefore, a conversion of *gluco*-thiol to *gluco*-disulfide was considerably sluggish under similar reaction conditions due to the unfavorable steric demands. After a successful conversion of water soluble (2→2) linked symmetric disulfides, we explored the utility of thiols for *S*-alkylations; which will be discussed in the next section.

4.2.2. *S*-Alkylations of 2-thiocarbohydrates

i) *S*-Methylations

To extend further the synthetic potential of 2-thiocarbohydrates, feasible transformations of 2-thiols, including *S*-alkylations and synthesis of thioglycosides were investigated. Among the various applications, organic sulfides attract a significant attention due to their stability, reactivity and ability to serve as precursors for the *C*-centered radicals.[28] In this context, 2-thiols were available as immediate substrates for functionalization of the carbohydrate linked sulfides *via* a number of approaches. Shown in the Scheme 4.2.2, a methyl thioether **39** was synthesized in good yield by an S_N2 reaction between thiol **16** and methyl iodide.



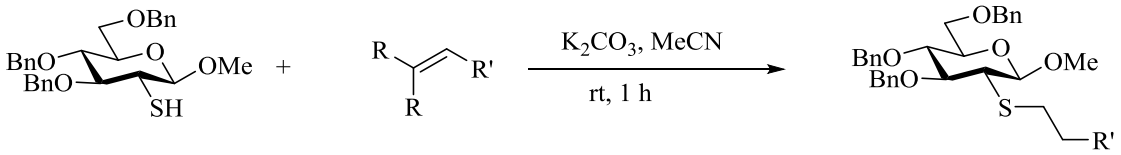
Scheme 4.2.2. Synthesis of the *S*-methyl derivatives.

However, further cleavage of the benzyl protecting groups by catalytic hydrogenation was failed due to the catalyst poisoning. Instead, a treatment of free thiol **24** with methyl iodide under slightly modified conditions established the protecting group free 2-thioether **40**.

ii) <u>Sulfa-Michael addition (SMA)</u>

Another convenient method to synthesize sulfides constitutes a conjugate addition of the thiol to suitable Michael acceptors, commonly known as sulfa-Michael addition (SMA).

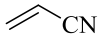
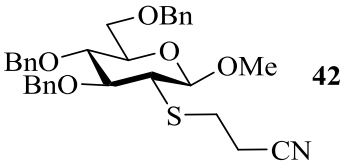
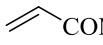
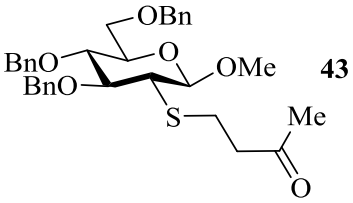
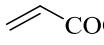
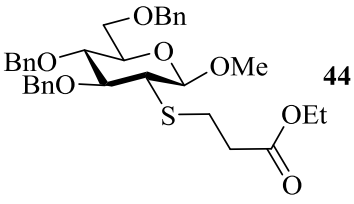
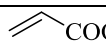
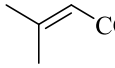
Table 4.2.3. Sulfa-Michael additions to the activated alkenes.



β-gluco-**16**

Alkenes (**41a–e**)
R = H, Me
R' = CN, COMe, COOEt, COOH

(42–44)

Entry	Alkene	Product	Yield(%)[a]
1	 **41a**	 **42**	83
2	 **41b**	 **43**	73
3	 **41c**	 **44**	83
4	 **41d**	No conversion	–
5	 **41e**	No conversion	–

[a] Yield of analytically pure products, isolated by column chromatography.

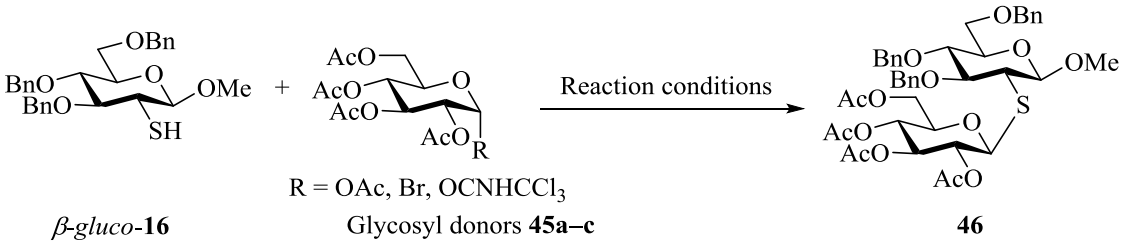
Combination of the acidic nature of thiols and enhanced nucleophilicity upon conversion to corresponding thiolates provides an efficient tool to construct a C-S bond under mild conditions.[58] Shown in the Table 4.2.3, various Michael acceptors **41a–e** were investigated for the synthesis of carbohydrate linked sulfides using model thiol **16**. Indeed, corresponding 2-sulfides **42**–**44** possessing terminal functional groups such as nitriles, ketones and esters were synthesized in moderate to good yields using this approach under basic conditions (entries 1–3). In contrast to these examples, addition of thiol to acrylic acid and dimethyl acrylic acid was unsuccessful (entries 4 and 5). A competitive addition of the carboxylate ion could interrupt the formation of thiolate by consumption of a base. The successfully synthesized sugar thioethers will be easily available for reductions, α-alkylations and further transformations. Structurally comparable 2-thio sugars could also be obtained by radical additions of the appropriate thiols to glycals; however low stereoselectivities, handling of smelly thiols and formation of deoxy sugars are major disadvantages.

iii) (2→1) Linked thiodisaccharides

The classical approaches for the synthesis of 2-thiodisaccharides are based on the reactions of 1-thiols with sugars containing the good leaving groups at the C-2 position; thus offering the (1→2) linked thiosugars.[59] A slightly modified strategy could offer an assembly of diversified thiosugars. Thus, as shown in the Table 4.2.4, suitable reaction conditions were optimized by coupling of the thiol **16** with various glycosyl donors for the synthesis of a 2-thiodisaccharide **46**. Glycosyl donors are functionalized sugars containing good leaving groups at the anomeric position; which can be activated by Lewis acid catalysis. Initially, glycosyl donors such as pentaacetyl glucose and the Schmidt imidate were investigated in the presence of catalytic amounts of Lewis acids. However, thiols were then either partially dimerized or decomposed under these reaction conditions and therefore failed to bring out the desired conversion (entries 1 and 2). Despite these glycosyl donors are most suitable components for chemical glycosylation, activation of the anomeric methoxy group could inadvertently occur at the thiol and diminish the reactivity. Subsequently, glycosyl halides were subjected to the glycosidation using promotors such as silver triflate or silver carbonate; however, thiols were found unreactive under these conditions as well (entry 3). From these observations, it could be figured out that Lewis acid

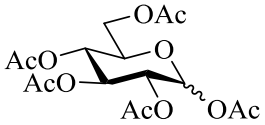
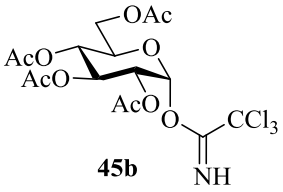
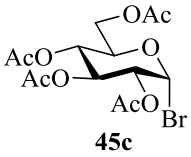
catalyzed glycosidations are unproductive with 2-thiols due to the low reactivity and interrupted activation of the glycosyl donors.

Table 4.2.4. Optimized synthesis of a thiodisaccharide **46**.



R = OAc, Br, $OCNHCCl_3$

β-gluco-**16** Glycosyl donors **45a–c** **46**

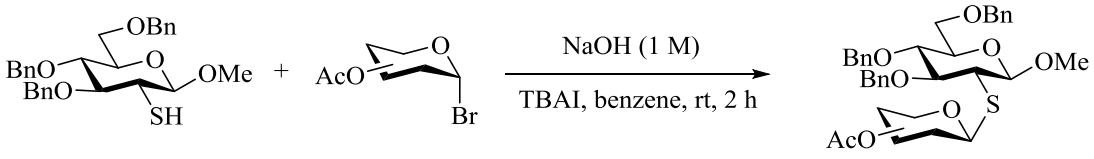
Entry	Glycosyl donor	Reaction conditions	Result[a]
1	 **45a**	$BF_3.Et_2O$, CH_2Cl_2, 0 °C, N_2	Incomplete conversion, slow reaction
2	 **45b**	a) $BF_3.Et_2O$, CH_2Cl_2, -15 °C, N_2	Decomposition of imidate
		b) TMSOTf, CH_2Cl_2, -15 °C, N_2	Dimer and many products
3	 **45c**	a) AgOTf, CH_2Cl_2, Sym collidine, -40 °C, N_2	Decomposition of thiol
		b) Ag_2CO_3, $CHCl_3$, rt, N_2	Decomposition of thiol
		c) Cs_2CO_3, DMF–DMSO, 0 °C, N_2, 2 h,	79%
		d) NaOH (1 M), benzene, rt, N_2, 2 h	85%

[a] Yield of analytically pure products, isolated by column chromatography.

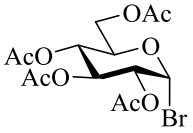
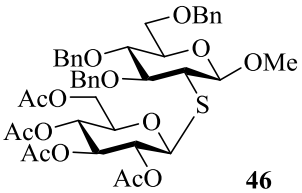
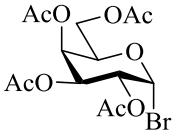
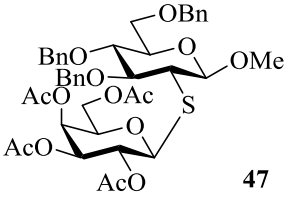
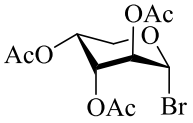
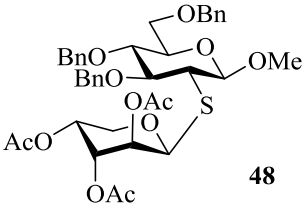
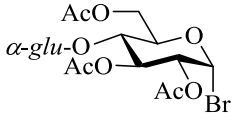
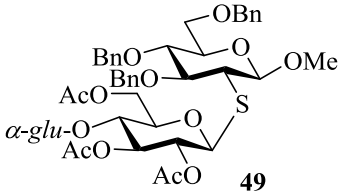
Subsequently, a base mediated nucleophilic displacement (S_N2) of glycosyl bromide by thiol **16** was carried out.[60] Interestingly, both cesium carbonate and sodium hydroxide/TBAI methods

successfully afforded a thioglycoside **46** with complete *β*-selectivity. The large coupling (J = 10.4 Hz) between the anomeric (H-7) and adjacent (H-8) protons of the second sugar counterpart unambiguously indicates the formation of the *β*-anomer. Shown in the Table 4.2.5, the corresponding (2→1) linked thiodisaccharides were successfully synthesized by the sodium hydroxide/TBAI method in the moderate to good yields with a consistent selectivity.

Table 4.2.5. Synthesis of the (2→1) linked thiodisaccharides.

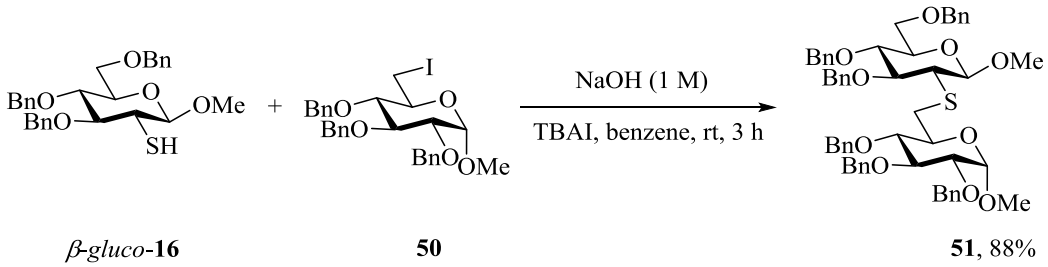


β-gluco-**16** Glycosyl donors **45c–f** **46–49**

Entry	Glycosyl donor	Product	Yield (%)[a]
1	 *gluco*-**45c**	 **46**	85
2	 *galacto*-**45d**	 **47**	80
3	 *arabino*-**45e**	 **48**	95
4	 *malto*-**45f**	 **49**	57

[a] Yield of analytically pure products, isolated by column chromatography.

From the mechanistic point of view, abstraction of the proton from the thiol group generates a thiolate ion; which reacts with glycosyl bromide to form the thiodisaccharide. Despite the excellent diastereoselectivities observed in all products, yields are affected by the steric reasons. For instance, reactions of sterically less hindered glycosyl bromides with the 2-thiosugars took place in good to excellent yields (entries 1–3); whereas, a reaction with bulky maltosyl bromide was proceeded with lower yield (entry 4). The moderate yield could be caused by the decomposition or displacement of the corresponding maltosyl bromide by the hydroxide ion. To explore the further scope of the methodology, a (2→6) linked thiodisaccharide **51** was synthesized. A coupling between *gluco*-thiol and the benzyl protected 6-iodo methyl glucopyranoside **50** was tried under same reaction conditions (Scheme 4.2.3).



β-gluco-**16** **50** **51**, 88%

Scheme 4.2.3. Synthesis of the (2→6) linked thiodisaccharide.

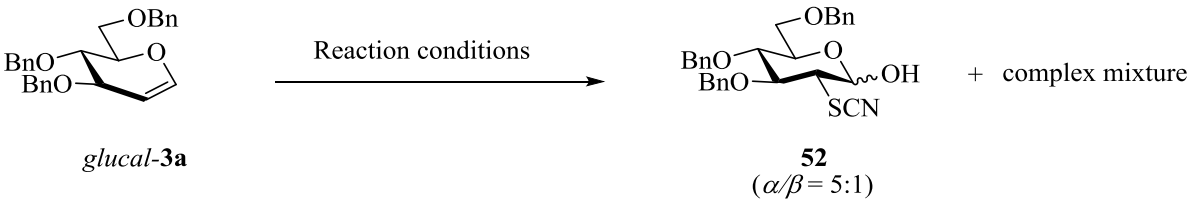
Similar to glycosyl bromides, the 6-iodo sugar undergoes nucleophilic substitution to afford a (2→6) linked thiodisaccharide in excellent yield. In all described examples, a stereochemical outcome of the resultant products can be easily established by NMR spectroscopy. To the best of our knowledge, these are the first examples of (2→1) and (2→6) linked thiodisaccharides, where 2-thiols are employed as starting materials. Having successfully developed new approaches for the synthetic transformations of 2-thiocarbohydrates; we were next interested in the functionalization at the anomeric center, which will be described in the next section.

4.2.3. Trapping of the oxocarbenium cation by water

CAN mediated thiocyanation at the C-2 position provides an access to 2-thiosugars from glycals in a single step. Since methanol functions as solvent as well as nucleophile, the overall scope of this novel approach was limited to the methyl glycosides. We were therefore interested to

develop a new strategy to trap the oxocarbenium ion by other nucleophiles. In the initial experiments, addition of NH_4SCN to glucal was carried out in the presence of water under different reaction conditions (Table 4.2.6). It turned out that a slow addition of CAN in acetonitrile resulted in incomplete conversion of glucal to the product (entry 1). Interestingly, fast addition of CAN to the reaction mixture was successful to consume the starting material within one hour; however only 37% of the desired addition product **52** along with a complex mixture of other products was obtained.

Table 4.2.6. Optimized synthesis of 2-thiocyanate **52**.



glucal-**3a**

52
(α/β = 5:1)

Entry	Reaction conditions	Time	Temperature	Result (%)[a]
1	CAN, MeCN:H_2O, NH_4SCN	-	rt	Incomplete conversion[b]
2	CAN, MeCN:H_2O, NH_4SCN	1 h	rt	37
3	CAN, MeCN:H_2O, NH_4SCN	1 h	0 °C	28
4	$(NH_4)_2S_2O_8$, $CuSO_4.5H_2O$, MeCN:H_2O, NH_4SCN	4 h	rt	31
5	$(NH_4)_2S_2O_8$, $CuSO_4.5H_2O$, MeCN:H_2O, NH_4SCN	5 h	0 °C	28
6	$K_2S_2O_8$, $CuSO_4.5H_2O$, MeCN:H_2O, NH_4SCN	6 h	rt	30

[a] Yield of analytically pure products, isolated by column chromatography.

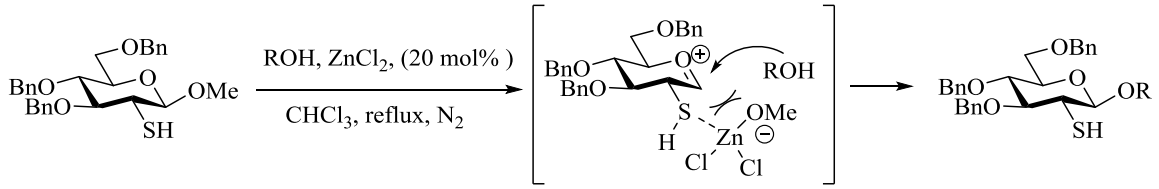
[b] Reaction was performed with a slow addition of CAN.

Even reaction at the low temperature couldn't be effective to improve the yield of main product (entries 2 and 3). The use of other oxidizing agents such as ammonium persulfate and potassium persulfate afforded relatively lower yields (entries 4–6). Formation of side products such as 2-deoxy sugars, the lactone and possible intramolecular cyclization to corresponding 1, 3-oxathiolan-2-imines could influence the yields; however these products haven't been isolated in pure form. Indeed, the yields are not satisfactory; thiocyanation took place presumably from the lower face and subsequent trapping of the oxocarbenium ion by water affords a mixture of anomers. The ^{1}H NMR analysis of product clearly indicates the formation of anomers with (α/β = 5:1) selectivity. Although poor yields were observed in initial findings, the scope of this approach could be expanded to other nucleophiles. Apart from introduction of various nucleophiles during the thiocyanate radical additions; modifications at the anomeric position of 2-thiols could be accessed by Lewis acid activation; which will be discussed in the next section.

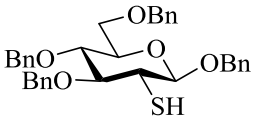
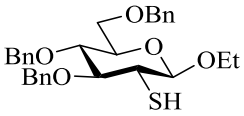
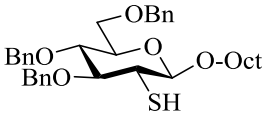
4.2.4. Lewis acid mediated transformations at the anomeric center

Most of the strategies to synthesize disaccharides are based on the activation of glycosyl donors such as imidates, thioglycosides or pentaacetyl sugars by suitable promotors. However, methyl glycosides are hardly explored for the glycosidation. Among the various factors, neighboring group participation and nature of the protecting groups play an important role in the stereochemistry and reactivity of chemical glycosidation. We were therefore interested to investigate the replacement of the methoxy group by other nucleophiles such as primary alcohols using a Lewis acid catalysis (Table. 4.2.6). Thus, thiol **16** was treated with different nucleophiles in the presence of catalytic zinc chloride to afford β-selective alkyl glycosides (entries 1–3). A typical large coupling (J = 8.5 Hz) between the anomeric and adjacent proton clearly indicates the formation of β-anomer. The exclusive selectivity in the glycosidation is found due to the activation of the methoxy group and blocking of the lower face by coordination of zinc catalyst with the thiol group. Thus, subsequently formed intermediate **53** prefers the attack of nucleophile from the upper site followed by regeneration of the catalyst to furnish β-thiols **54**–**56** in good yields.

Table 4.2.6. Transformations of the methyl glycosides to alkyl glycosides.



β-gluco-**16** **53** **54–56** (selectively *β*)

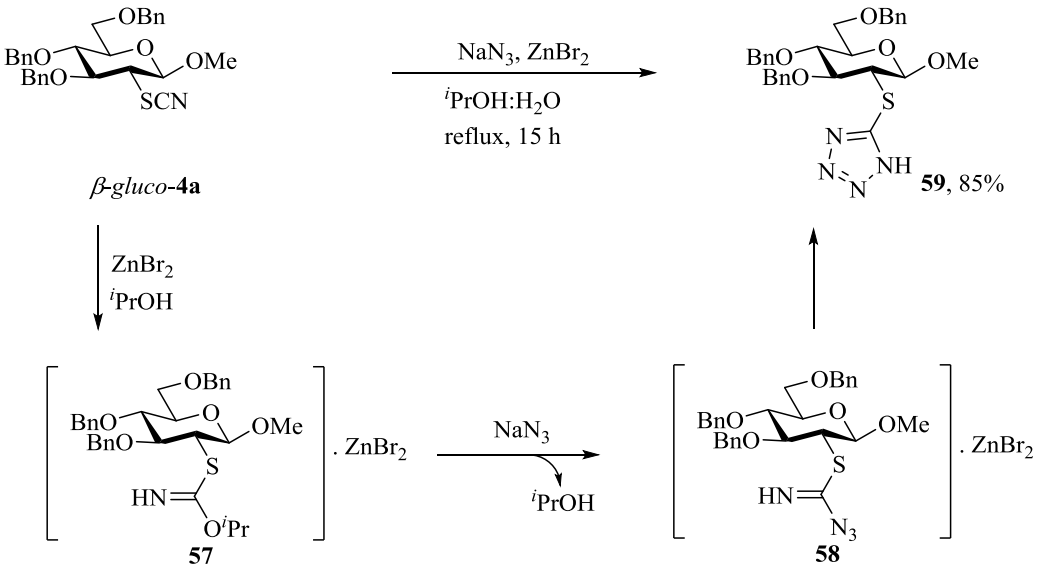
Entry	Nucleophile	Time	Product		Yield (%)[a]
1	BnOH	3 h		**54**	83
2	EtOH	7 h		**55**	77
3	OctOH	6 h		**56**	81

[a] Yield of analytically pure products, isolated by column chromatography.

4.2.5. Transformations of 2-thiocyanates

i) (3 + 2) Cycloaddition

Next, we investigated the synthetic potential of easily available 2-thiocyanates towards the synthesis of sugar containing heterocycles and modifications at the anomeric center. The well-studied cycloaddition between 1,3-dipoles and dipolarophiles facilitates a convenient entry to five membered heterocycles. For instance, cycloadditions between alkynes and the azides afford triazoles in excellent yields and with high regioselectivity.[61] Analogous to the classical (3 + 2) cycloadditions, similar reaction conditions could also be applied to obtain a regioselective access to the thio-tetrazoles using thiocyanates.[62] Although, thiocyanates are structurally different from alkynes, a slight resemblance with the triple bond of the nitrile functionality serves them as excellent dipolarophiles. Thus, we demonstrated an example of cycloaddition between *gluco*-**4a** and sodium azide (Scheme 4.2.4).

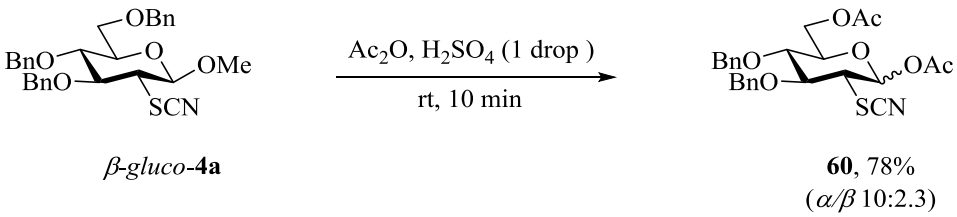


Scheme 4.2.4. Cycloaddition between 2-thiocyanate *β-gluco*-**4a** and sodium azide.

In the first step, zinc-catalyzed reaction of thiocyanate with isopropanol forms the corresponding imino ether **57**; which subsequently reacts with sodium azide to form a thiotetrazole **59** *via* azido intermediate **58**. The formation of thiotetrazole can be easily confirmed by a signal around δ 10 ppm for N*H* proton in the ^{1}H NMR spectrum. To the best of our knowledge, this reveals the first example for a carbohydrate linked thiotetrazole.

ii) <u>Trapping of the anomeric center by water</u>

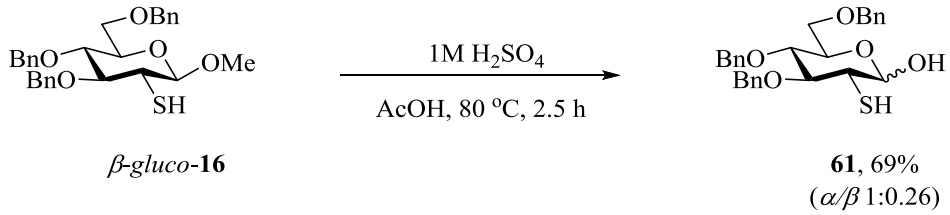
Next, the stability of 2-thiocyanates under acidic conditions was explored. In general, methyl group serves as a stable protecting group under basic conditions; whereas, reducing sugars can be obtained under strongly acidic conditions. Methyl glycosides can be hydrolyzed by the treatment of concentrated sulfuric or hydrochloric acid.[63] In the following experiments, 2-thiocyanates were treated with a catalytic amount of sulfuric acid to convert into the corresponding acetyl sugar (Scheme 4.2.5).



Scheme 4.2.5. Trapping of the oxocarbenium ion by the acetoxy group.

It was anticipated to cleave the methoxy group under such strongly acidic conditions; however no conversion occurred. Therefore, in the modified approach, a newly formed hydroxyl group was trapped by acetic anhydride to give a mixture of (α/β 10:2.3) acetoxy glycosides. Additionally, it turned out that the benzyl group at the C-6 position also undergoes cleavage followed by trapping to form a 1,6-diacetyl sugar **60** in good yield. Interestingly, the stability of thiocyanate group under strong acidic conditions expands the scope of transformations for the acid sensitive thiosugars.

In the similar way, 2-thiols could also be transformed into reducing sugars by the treatment of strong acids. The treatment of 1 M sulfuric acid was successful to convert methyl glycosides to a mixture of (α/β 1: 0.26) hydroxyl glycosides **61** by hydrolysis (Scheme 4.2.6).



β-gluco-**16**

61, 69%
(α/β 1:0.26)

Scheme 4.2.6. Trapping of the oxocarbenium ion by water.

4.2.6. Summary

In summary of this chapter, we successfully explored simple synthetic transformations of the 2-thiocarbohydrates from a different perspective. For instance, thio-functionalization of carbohydrates at the C-2 position could be achieved by nucleophilic substitutions or thiyl radical additions to the glycals. However, these approaches are tedious due to elements such as reactivity, choice of reagents and the stereochemical and structural outcome in the final products. For the first time, easily available 2-thiols were successfully utilized as precursors for the synthesis of carbohydrate linked sulfides as well as thiodisaccharides at the C-2 position. For example, 2-sulfides were obtained by sulfa-Michael addition (SMA) to the electron deficient olefins possessing terminal functional groups. *S*-methylations were carried out with protected as well as free thiols under appropriate reaction conditions. Furthermore, iodine mediated oxidations of the thiol group to symmetric disulfides were carried out for the first time. Also, formation of water soluble disulfides and related steric factors were discussed in details. Synthetically more valuable approaches were developed to obtain an access to the

thiodisaccharides by a coupling between 2-thiols and corresponding halo-sugars in good to excellent yields. Additionally, 2-thiols were subjected for the functionalization at the anomeric position by means of Lewis acid catalysis; where methyl glycosides were converted to the alkoxy glycosides. It would be worth noting that transformations such as synthesis of thiodisaccharides and replacement of the methoxy group by alcohols in the presence of competitive internal nucleophiles took place with a high selectivity providing only a single product. Thus, the synthetic potential of these approaches was enhanced by introducing entries to the (2→1), (2→6) and (2→2, disulfides) linked thiocarbohydrates. In the second part of the studies, 2-thiocyanates were subjected to the trapping of the anomeric position by acetic anhydride. Furthermore, a 2-*S* linked heterocycle was synthesized by the (3 + 2) cycloaddition between the thiocyanate and azide. Finally, trapping of the oxocarbenium cation by water to form a reducing sugar was investigated to demonstrate the diversity in the thiocyanate radical additions to glycals. Alternatively, 2-thiocyanates as well as 2-thiols were investigated for the synthesis of reducing sugars; which could be useful further to synthesize *O*-glycosides possessing the sulfur functionality at the C-2 position. In short, these studies demonstrated the first examples of 2-thiocarbohydrates with divergent functionalizations. In order to extend the scope of 2-thiocarbohydrates towards the synthesis of thiodisaccharides, we explored the thiol-ene coupling. The photochemical addition of 2-thiyl radicals to three different *exo*-glycals and details thereof will be discussed in the next chapter.

(Chapter 3)

Synthesis of thiodisaccharides *via* thiol-ene coupling

In this chapter, photochemical addition of the 2-thiyl radicals to *exo*-glycals will be discussed. Apart from the nucleophilic substitution, a radical based thiol-ene coupling (TEC) became an attractive method to synthesize thiodisaccharides with excellent stereoselectivities. This particular area of research has opened huge opportunities to develop new carbohydrate entities, which are important from the biological perspective.[34] In the present work, 2-thiols were treated with *exo*-glycals to obtain corresponding thiosugars in good to excellent yields. In the following sections, optimization of the substrates and reaction conditions, the reaction mechanism and stereoselectivity will be described.

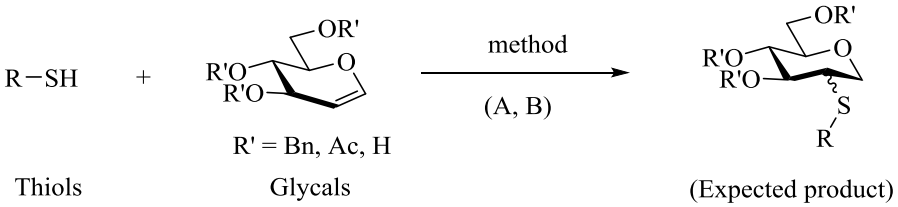
4.3.1. Screening of the substrates for thiol-ene coupling

To construct a thioether linkage between two carbohydrates, 2-thiols were subjected for radical additions to glycals. Although, radical additions of the sterically less hindered glycosyl thiols to glycals are known in literature; we were specifically interested to investigate the reactions of sterically more crowded thiols.[64] Thiyl radicals are readily generated from the sulfur containing molecules such as thiols or disulfide under suitable radical conditions. Consequently, generation of the 2-thiyl radicals can be achieved either photochemically, thermally or by a redox way; the preliminary experiments were carried out under photochemical reaction conditions. Amongst the number of photocatalysts available, 2,2-dimethoxy-2-phenylacetophenone (DPAP) was chosen as a radical initiator due to the facile activation upon UV irradiation at room temperature. It is worth mentioning that the reversibility of thiyl radical additions to sterically hindered glycals could diminish the reactivity. Therefore, screening for the suitable reaction conditions was necessary in the case of sterically crowded substrates.

Reactions between various thiols and *endo*-glycals have been examined as a first approach to optimize the reaction conditions and substrates (Table 4.3.1). A model reaction between thiol **16** and benzyl protected glucal **3a** was carried out in the presence of DPAP; however, no conversion was observed over a prolonged reaction time. Increasing the amount of thiol by 6 folds with respect to glucal couldn't show any progress in the reaction. Thus, it was anticipated that the steric effects generated by the bulky benzyl groups present on both substrates restricts the addition of thiyl radicals. Next, the sterically less crowded glycals were investigated; however,

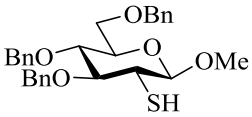
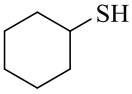
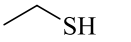
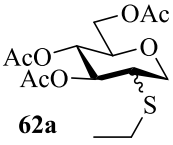
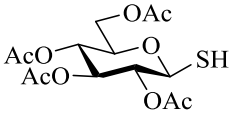
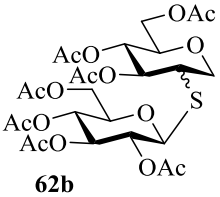
replacement of the protecting groups in glycals did not result in the addition products. Even switching to the thermal conditions in the presence of catalytic amounts of azobisisobutyronitrile (AIBN) was unsuccessful (entry 1). The reversibility in the addition of the initial 2-thiyl radical to glucal could also interrupt the propagation step; thus, no progress was observed.

Table 4.3.1. Optimization of the substrates and reaction conditions.



Method A: 2,2-dimethoxy-2-phenylacetophenone (DPAP), DCM/EtOH 4:1, *hv*.

Method B: azobisisobutyronitrile (AIBN), benzene, reflux.

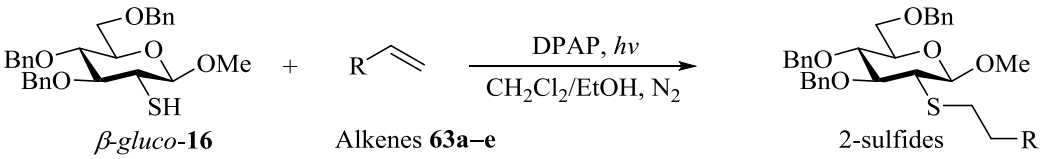
Entry	Thiol	Glucal	Method	Product	Result[a]
1	 **16**	Bn, Ac, H	A, B	–	no conversion
2	 **16a**	Bn, Ac	A, B	–	no conversion
3	 **16b**	Bn, Ac	A, B	–	no conversion
4	 **16c**	Ac	A	 **62a**	58%[64a], (major)
5	 **16d**	Ac	A	 **62b**	80%[64b], $\alpha/\beta = 41{:}59$

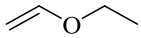
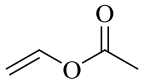
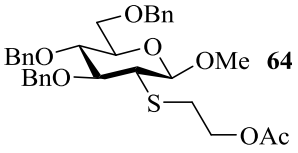
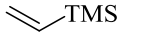
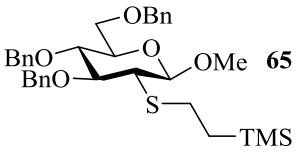
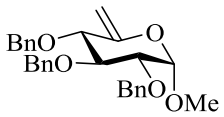
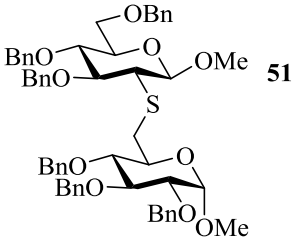
[a] Yield of analytically pure products, isolated by column chromatography.

In the next approach, non-sugar thiols were treated with glycals to check the impact of overall steric hindrance. It was turned out that the sterically crowded thiols such as tertiary butyl thiol and cyclohexanethiol were unreactive for the radical additions (entries 2 and 3). In contrast to these results, additions of thiols such as ethanethiol and glycosyl thiol to acetyl protected glycals at the C-2 position are functioning well under similar reactions conditions (entries 4 and 5).[64] From these observations it was clear that not only the protecting groups, but substitution at the double bond in *endo*-glycals also creates a steric hindrance, which in turn impairs the addition of 2-thiyl radicals. Thus, it predicts that the *exo*-glycals are more suitable coupling partners for the TEC, but the structural compatibility is favorable only with sterically less hindered thiols. The rationale behind these structural restrictions might be the weak orbital interactions between the SOMO of the bulky thiyl radicals and the HOMO of the glycals. Therefore, it was necessary to screen the alkenes, which can react effectively with 2-thiols.

In the following experiments, 2-thiols were examined for radical additions to various alkenes under photochemical conditions (Table 4.3.2). Initially, 3,4-dihydro-2*H*-pyran was chosen as a simple alkene, which structurally resembles the *endo*-glycals. Despite of bearing no protecting or hydroxyl groups, the expected radical addition to pyran failed. Therefore, *endo* enol ethers were not suitable substrates for the 2-thiyl radical additions (entry 1). In a modified approach, 2-thiols were treated with terminal alkenes possessing less steric hindrance. Despite of consisting structural simplicity and lower steric hindrance as compared to the cyclic enol ethers; surprisingly, no conversion was observed even in the case of acyclic ethyl vinyl ether. A competitive polymerization of vinyl ether over the addition of thiyl radicals could interrupt the progress of TEC (entry 2). In contrast to these results, additions of the thiol **16** to the terminal alkenes such as vinyl acetate and allyltrimethylsilane successfully occurred in a regioselective manner, affording the 2-sulfides **64** & **65** in good yields (entries 3 and 4). These findings strengthen the possibility of utilization of 2-thiols for the targeted thiol-ene coupling with suitable glycals accomplishing the structural demand. For this purpose, particularly *exo*-glycals are quite attractive substrates to obtain a structural diversity in the addition products. A highlighting difference between the *endo*- and *exo*-glycals concerning the position of double bond affects the addition of bulky thiyl radicals. Therefore, sterically less hindered *exo*-glycals were used for the further optimization.

Table 4.3.2. Screening of the alkenes for the thiol-ene coupling.



Entry	Alkenes	2-sulfide	Time (h)	Yield (%)
1	 **63a**	–	–	No conversion
2	 **63b**	–	–	No conversion
3	 **63c**	 **64**	1	82
4	 **63d**	 **65**	3	68
5	 **63e**	 **51**	6	89[b]

[a] Yield of analytically pure products, isolated by column chromatography.

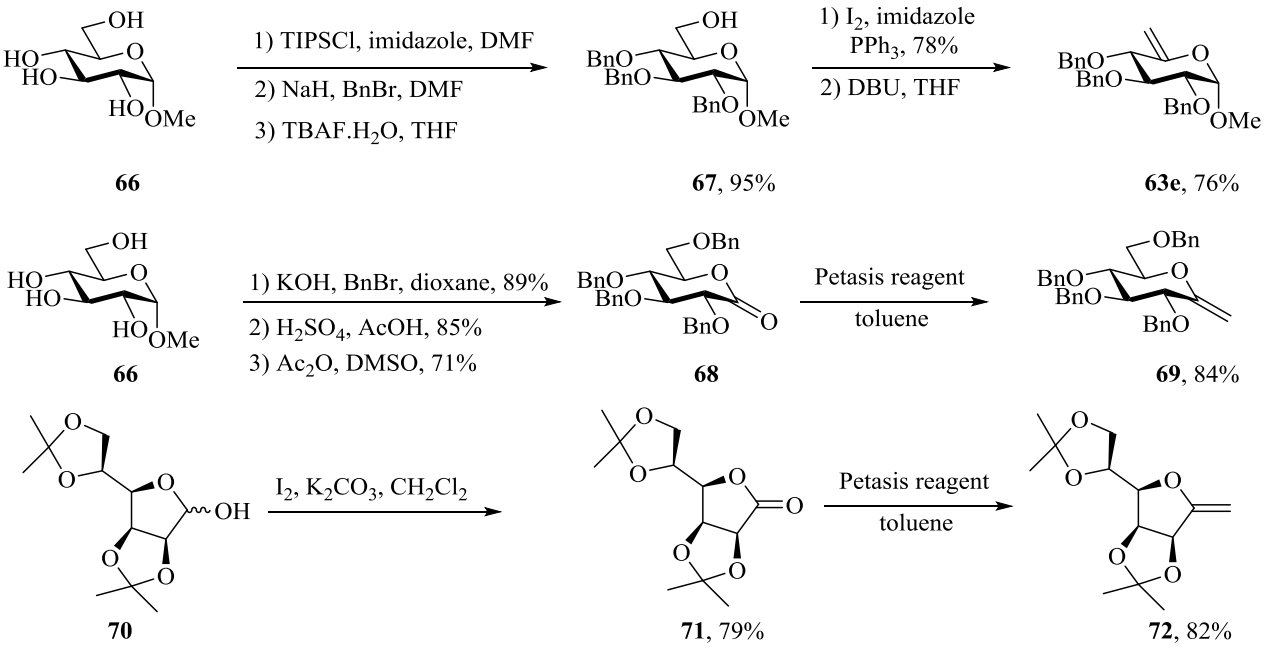
[b] Also synthesized by nucleophilic substitution between the thiol **16** and 6-iodosugar **50**.

Interestingly, addition of the thiol **16** with *exo*-glycal **63e** took place smoothly to afford a (2→6) linked thiodisaccharide **51** in *anti*-Markovnikov fashion (entry 5). High regioselectivity for the addition product is observed due to the stabilization of a carbon centered radical intermediate by an adjacent oxygen atom at the carbohydrate ring. Thus, analogous to the terminal alkenes, carbohydrates possessing an *exo* double bond are potential substrates for additions of the bulky thiyl radicals. Finally, the suitable reaction conditions consisting 1.5 fold excess of thiols relative to alkenes and dichloromethane/ethanol as the solvent were applied for the subsequent studies.

4.3.2. Radical additions of the 2-thiols to *exo*-glycals

i) Syntheses of the *exo*-glycals

To extend the synthetic utility of the methodology, three different *exo*-glycals were synthesized according to the literature known procedures with minor modifications (Scheme 4.3.1).[65]



Scheme 4.3.1. Syntheses of the exo-glycals.

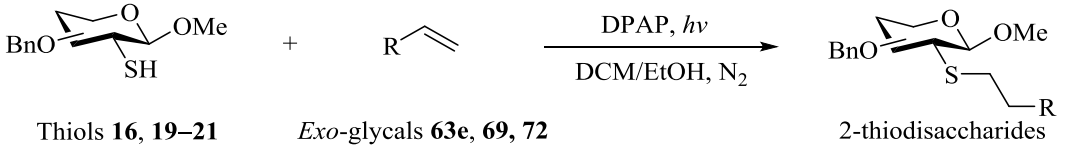
The *exo*-glycal **63e** was synthesized from a commercially available methyl glucopyranoside **66**; where a key step in formation of the *exo* double bond at the C-5 position involved a base mediated elimination of hydrogen iodide from a 6-iodo precursor. On the other hand, *exo*-glycals **69** and **72** containing the double bond at the anomeric position were synthesized from corresponding lactone precursors by the Petasis olefination method. These three different types of *exo*-glycals generate a broad scope of the starting materials for the synthesis of asymmetric 2-thiodisaccharides.

ii) TEC between the 2-thiols and *exo*-glycals

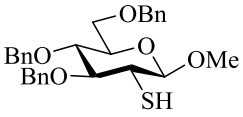
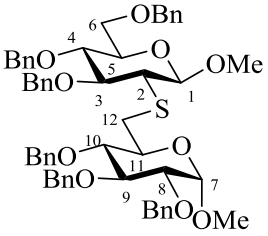
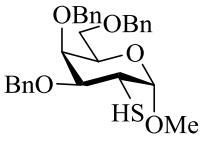
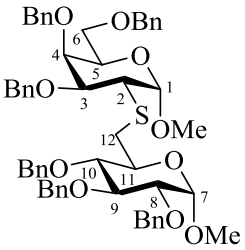
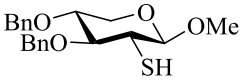
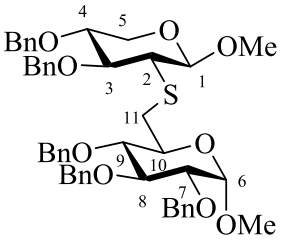
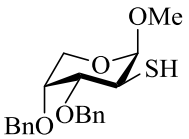
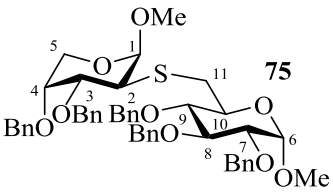
To extend the synthetic potential of photoinduced TEC, 2-thiols were treated with *exo*-glycals under UV irradiation (λ = 365 nm) in the presence of catalytic DPAP (Table 4.3.3). In the first

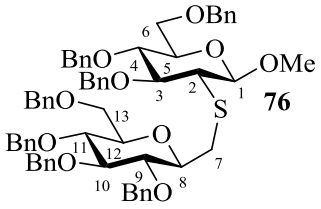
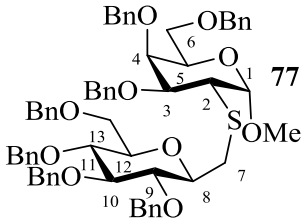
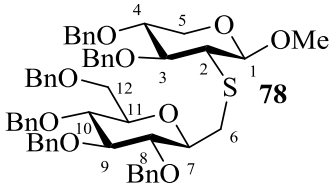
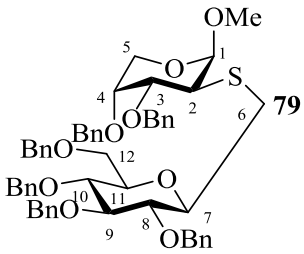
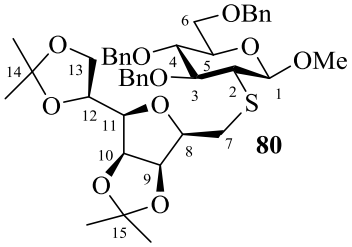
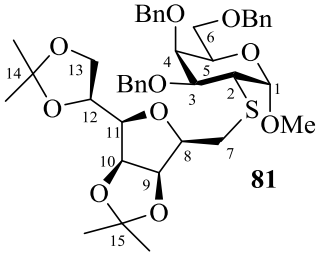
set, reactions between thiols and C-5 *exo*-glycal **63e** were effective to synthesize the (2→6) thiodisaccharides in moderate to excellent yields (entries 1–4). Interestingly, all reactions proceeded with high regio- and diastereoselectivities.

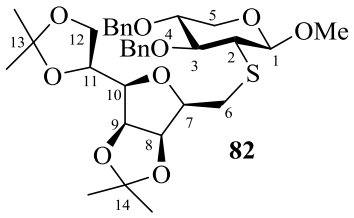
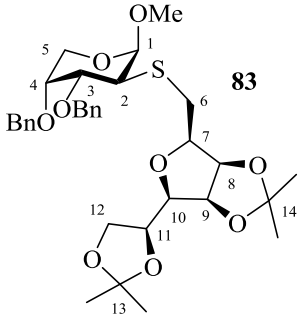
Table 4.3.3. Addition of 2-thiols to the *exo*-glycals



Thiols **16**, **19–21** *Exo*-glycals **63e**, **69, 72** 2-thiodisaccharides

Entry	Thiol	*Exo*-glycal	Time (h)	2-thiodisaccharide	Yield (%)
1	 *β-gluco*-**16**	**63e**	6	 **51**	94
2	 *α-galacto*-**19**	**63e**	8	 **73**	75
3	 *β-xylo*-**20**	**63e**	8	 **74**	76
4	 *β-arabino*-**21**	**63e**	8	 **75**	74

5	*β-gluco*-**16**	**69**	2.5	 **76**	80
6	*α-galacto*-**19**	**69**	5	 **77**	90
7	*β-xylo*-**20**	**69**	3	 **78**	74
8	*β-arabino*-**21**	**69**	4.5	 **79**	66
9	*β-gluco*-**16**	**72**	1	 **80**	79
10	*α-galacto*-**19**	**72**	4	 **81**	64

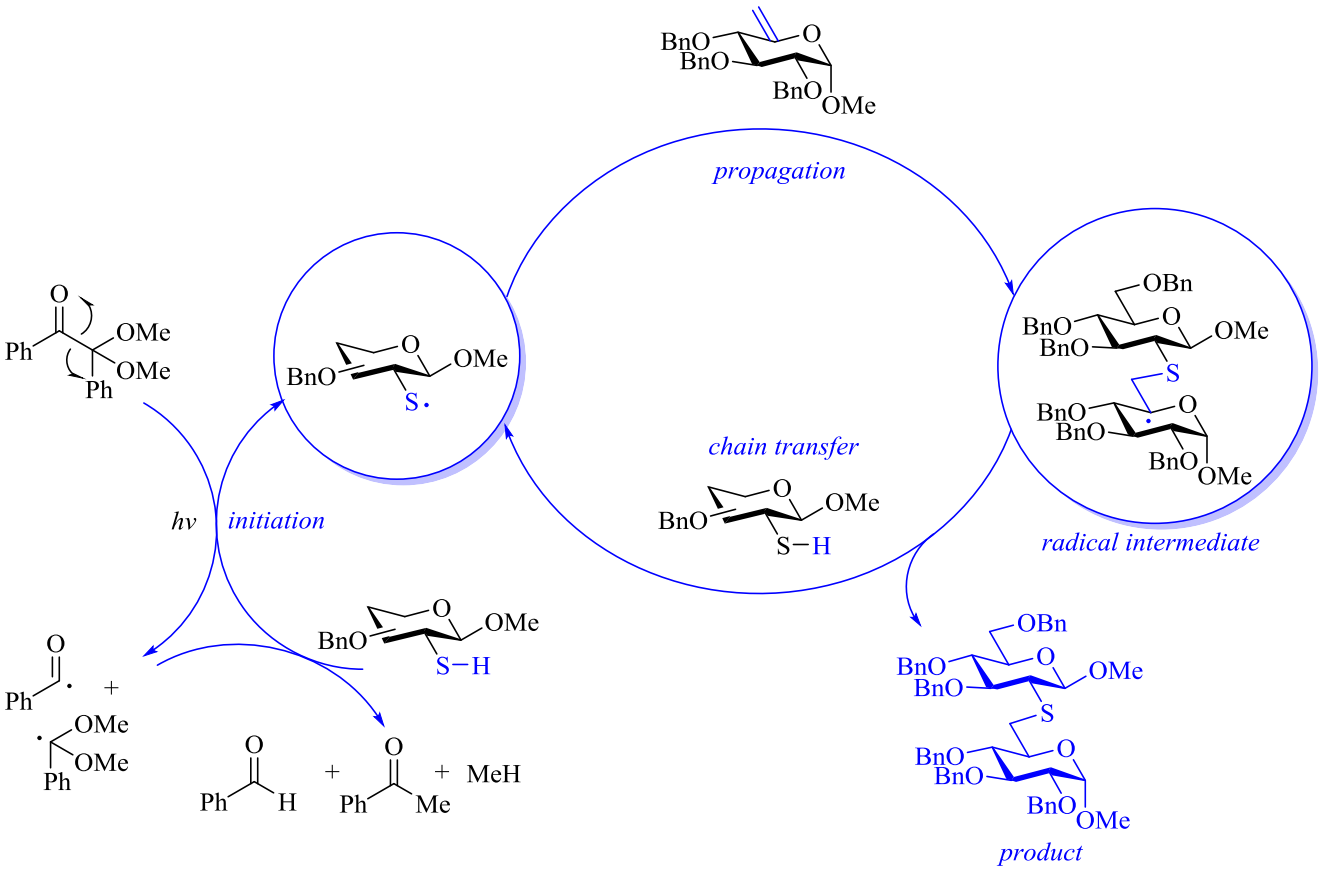
11	*β-xylo*-**20**	**72**	4	 **82**	86
12	*β-arabino*-**21**	**72**	3	 **83**	87

[a] Yield of analytically pure products, isolated by column chromatography.

Subsequently, *exo*-glycals possessing the double bond at the anomeric position were treated with 2-thiols. Indeed, all coupling products were obtained in moderate to excellent yields along with similar stereoselectivities to those observed for the C-5 *exo*-glycal (entries 5−12). Nonetheless, the corresponding 2-thiyl radical additions were faster in the case of anomeric *exo*-glycals as compared to the *exo*-glycal **63e**. Finally, the structural assignments were unambiguously performed by advanced analytical methods. For example, the large couplings around (J = 13.9 Hz) for the germinal protons present on the thio-methylene group confirm a thiodisaccharide formation in all addition products. The small couplings around 2.6 Hz between the anomeric and the adjacent proton from the second sugar counterpart confirms *β*-selectivity in the addition products. More detailed structural analysis was carried out by the NOESY experiment. For example, the cross peak between the protons (7-H) and (8-H, 9-H, 10-H) with *cis*-relationship indicates the formation of new bond from the *β*-face in thiodisaccharide *β-arabino*-**83**. Indeed, the successful additions of the bulky 2-thiyl radicals to the *exo*-glycals are based on the stability of the radical intermediates formed after addition of the first thiyl radical. A plausible reaction mechanism for the addition of the 2-thiol to the typical *exo*-glycal will be discussed in the next section.

4.3.3. Proposed reaction mechanism for the thiol-ene coupling

Generally, the thiol-ene coupling has been conducted under radical conditions, often photochemically induced preferred due to ease in the activation of the radical initiator. Functionalization of the *exo*-glycals by thiol-ene addition proceeds by a radical chain transfer process.[64a] Shown in the Scheme 4.3.2, a typical reaction mechanism for hydrothiolation involves three steps including the initiation, propagation and termination.



Scheme 4.3.2. A plausible reaction mechanism for the TEC.

In the first step, the reaction is initiated by a photolytic cleavage of the photoinitiator-DPAP followed by the abstraction of a hydrogen atom to form a thiyl radical. In the first propagation step, this *in situ* generated 2-thiyl radical undergoes addition to the *exo*-glycals selectively in the *anti*-Markovnikov fashion, i.e. at the terminal site of the double bond and subsequently generates the carbon centered radical intermediates as shown in the Figure 4.3.1.

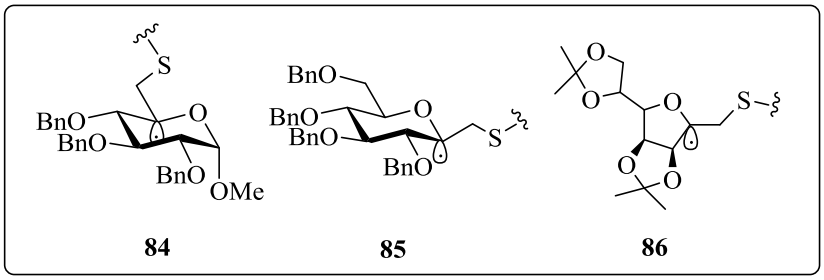


Figure 4.3.1. Carbon centered radical intermediates after the addition step.

The radical cycle continues *via* a chain transfer process by regenerating the thiyl radicals from fresh thiols in the succeeding propagation steps. The stereochemical control in the addition products is delivered by the abstraction of the hydrogen from the lower face. Thus, formation of the new C-C bond takes place from the upper face in all described thiodisaccharides. In the last step, termination could take place by two ways including the recombination of thiyl radicals to disulfides and carbon centered radical intermediates to the corresponding dimers.

4.3.4. Summary

In summary of this chapter, we successfully developed a methodology to synthesize thiodisaccharides *via* thiol-ene coupling. While screening the suitable reaction conditions, it was observed that the steric demands of the substrates play an important role in the bulky 2-thiyl radical additions to glycals. As compared to the photoinduced additions of glycosyl thiols to the *endo*-glycals, sterically more hindered thiols such as *tert*-butylthiol, cyclohexanethiol and 2-thiols were found unreactive. On the other hand, additions of 2-thiols were successful to the terminal alkenes such as vinyl acetate and allyltrimethylsilane owning to the minimum steric crowd. Surprisingly, in the case of vinyl ether no addition was observed due to the predominant polymerization over the TEC. From all experiments carried out, it has become abundantly clear that the radical additions of 2-thiols are influenced more by steric factors than the electronic factors. Additionally, reversibility of the thiyl radical addition to bulky alkenes could also restrict the first propagation step. Therefore, it can be concluded that at least one of the components has to be sterically less crowded to establish the favorable orbital interactions between the 2-thiols and corresponding alkenes.

In the second part of the studies, *exo*-glycals were found as suitable coupling components for the 2-thiyl radical additions under photochemical reaction conditions. Indeed, the thiyl radical

additions to the C-5 *exo*-glycals afforded (2→6) linked thiodisaccharides, whereas the anomeric *exo*-glycals ended up with the thiomethylene glycosides (2→SCH_2-1). A synthetic potential of thiol-ene coupling to *exo*-glycals with a total regio- and diastereoselectivity offers new entries for the synthesis of 2-S linked disaccharides. For the first time, functionalization of the 2-thiols for a synthesis of thiodisaccharides by radical additions marked their scope from a divergent and comprehensive viewpoint. Finally, it could be fundamental to underline the significance of possible applications of this approach for the synthesis of carbohydrate mimics comprising the sulfur atom at various positions in their core structure. The future outlook with possible new strategies including thiol-disulfide exchange, investigations of closely bound carbohydrate-gold nanoparticles, binding studies with biomolecules and a comprehensive scope of the thiocarbohydrates in organic synthesis will be discussed in the next chapter.

5. Future outlook

Binding studies

The synthetic potential of 2-thiocarbohydrates can be further explored with new approaches. For instance, the binding studies of carbohydrates with lectins can be performed with 2-thio analogs of the naturally occurring sugars. Lectins are the proteins, which are known to bind with specific carbohydrates and in turn allow the cell-carbohydrate interactions. Our recent studies found a stronger binding affinity for concanavalin A with *α-manno*-**17** as compared to the natural methyl mannopyranoside; thus, these studies could be extended for other 2-thiocarbohydrates.[53]

Sugar-gold nanoparticles

Thiosugar-modified gold nanoparticles are useful to investigate the carbohydrate-protein interactions and carbohydrate-carbohydrate recognitions. In the classical approaches, long chain sugar thiols are employed for the preparation of carbohydrate covered gold nanoparticles. As compared to them, closely bound thiosugar-gold nanoparticles could be synthesized from 2-thiols, which might show altered binding properties with biomolecules (Figure I).

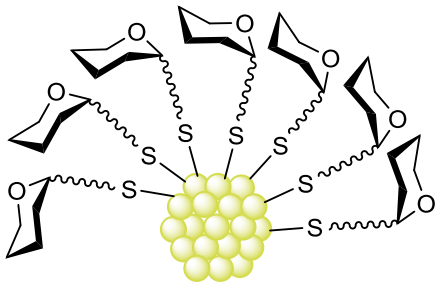
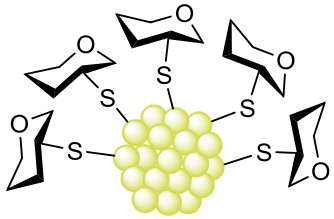


Figure I. Carbohydrate covered gold nanoparticles inked through a long chain spacer

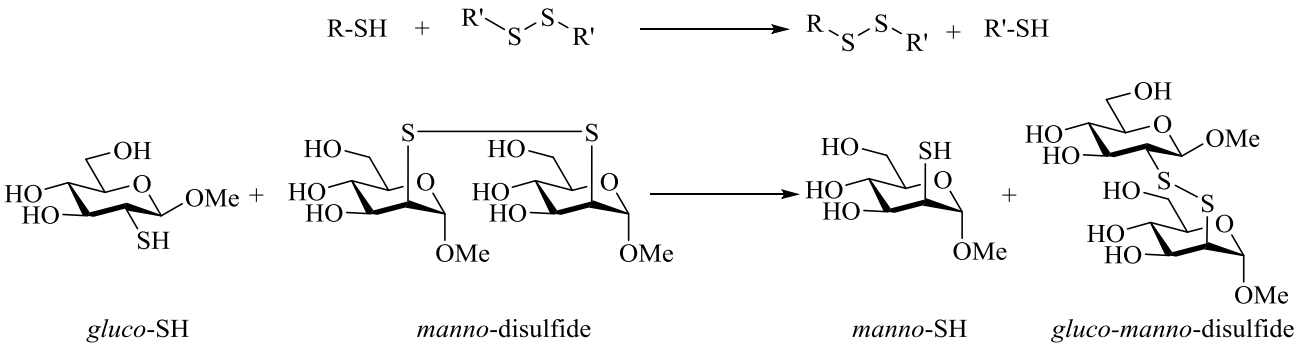


Closely bound carbohydrate covered gold nanoparticles

Thiol-disulfide exchange

Thiol-disulfide exchange is a formation of a new disulfide bond by reaction of a thiolate with disulfide. This reaction plays an important role in stabilization of protein structures and various enzymatic processes. In this context, 2-thiols can be explored for the thio-disulfide exchange

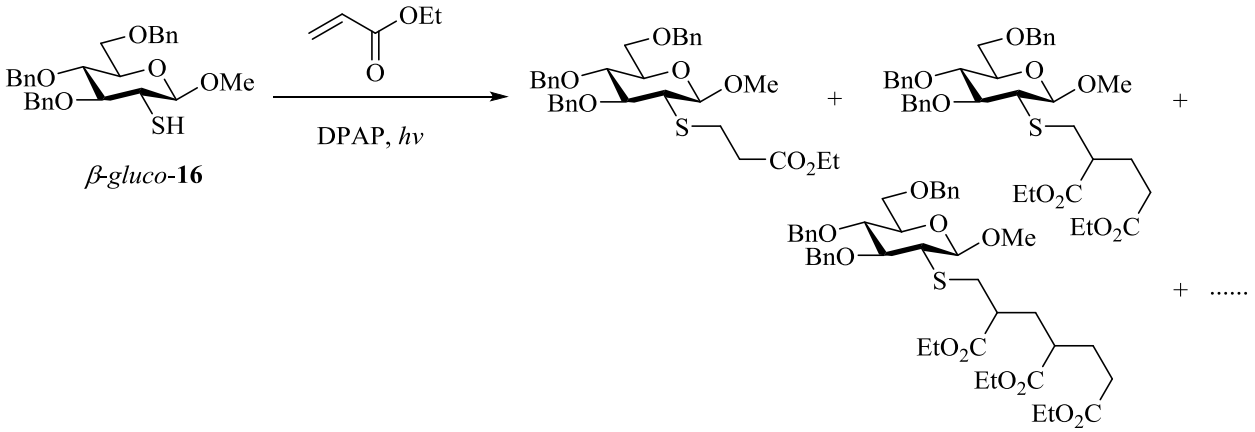
studies (Scheme I). For example, the reaction of *gluco*-SH with symmetric *manno*-disulfide could generate the asymmetric *gluco-manno*-disulfide by releasing the *manno*-SH unit; thus, *gluco*-SH can act as a reducing agent.



Scheme I. Thiol-disulfide exchange.

Thiosugar based oligomers

Thiol-ene chemistry became an important tool to synthesize thiodisaccharides under mild reaction conditions. The diverse application focusing the addition of 2-thiols to suitable substrates such as acrylates or acrylonitrile could be useful to synthesize thiosugar based polymers. For instance, the photochemical addition of thiol **16** to the excess of ethyl acrylate could undergo the extended chain process to synthesize thiosugar linked polymers (Scheme II).



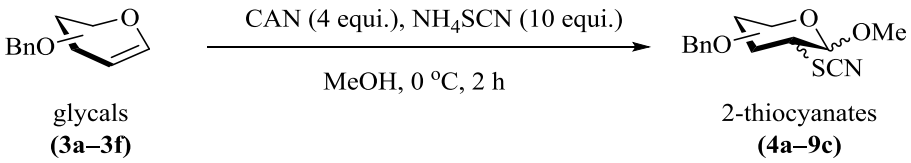
Scheme II. Thiosugar based polymers.

6. Experimental section

General information

All compounds were used as purchased without further purification. Unless otherwise stated, all reactions were carried out under nitrogen atmosphere in dry glassware with dried solvents. ^{1}H NMR and ^{13}C NMR were recorded on a Bruker Avance 300, Bruker Avance 500 or Bruker Avance 600 and analyzed with Top Spin. 2D experiments (HMQC, NOESY, HSQC and coupled HSQC) were performed to assign the chemical shifts and to determine the C−H coupling constants. Chemical shifts (δ-scale) are reported in ppm with TMS (0 ppm) as internal standard for ^{1}H NMR and the residual solvent signals ($CDCl_3$: 7.26, D_2O: 4.79, CD_2Cl_2: 5.32 ppm) for ^{1}H NMR and ($CDCl_3$: 77.0 ppm) for ^{13}C NMR. Thin layer chromatography (TLC) was performed on silica coated TLC plates from Merck and visualized under UV light (at 254 nm); detection was carried out by charring with (sulfuric acid: ethanol: 3-methoxy phenol = 09:99:0.1) solution. Elemental analyses were performed on a vario EL III analyzer from Elementar. IR spectra were recorded on a Nicolet 6700 FT-IR spectrometer with ATR. Optical rotations were measured on JASCO P-1020 digital polarimeter at 589 nm. HRMS were recorded on an ESI-Q-TOF maXis mass spectrometer from Bruker Daltonik and EI on GC-TOF-micro mass spectrometer from Waters Inc. Melting points were measured on Stuart SMP11 apparatus (uncorrected). Heraeus UV-lamp (TQ 150-56001725) was used for the photochemical reactions.

General procedure for the addition of ammonium thiocyanate to glycals (3a–3f).



glycals **(3a–3f)** — 2-thiocyanates **(4a–9c)**

A solution of appropriate glycal[46] **3a**–**3f** (5 mmol) in methanol (50 mL) was cooled to 0 °C. At this temperature, a solution of ceric ammonium nitrate (10. 96 g, 20 mmol, 4 equiv) in methanol (100 mL) and a solution of ammonium thiocyanate (3.91 g, 50 mmol, 10 equiv) in methanol (100 mL) was added simultaneously using two separate addition funnels within 2 h until TLC showed complete conversion. The reaction mixture was further stirred for 30 min and quenched by an ice-cold solution of sodium sulfite (50 mL) and extracted with dichloromethane (3 × 80 mL). The

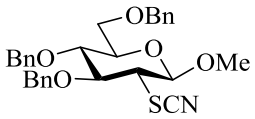
combined organic extracts were dried over sodium sulfate, concentrated and purified by silica gel column chromatography (hexane/ethyl acetate 80:20) to afford the 2-thiocyanates **4a**–**9c** in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-glucopyranoside (*β-gluco*-4a):

Nature = Colorless viscous oil (1.11 g, 44%).

R_f = 0.51 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +96.3 (c = 1.00 in $CHCl_3$).



β-gluco-**4a**

^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.83 (dd, *J* = 10.5, 8.5 Hz, 1 H, 2-H), 3.43 (ddd, *J* = 11.8, 5.7, 2.7 Hz, 1 H, 5-H), 3.53 (s, 3 H, O*Me*), 3.62–3.72 (m, 4 H, 3-H, 4-H, 6-H, 6'-H), 4.36 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.46 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 11.0 Hz, 1 H, *CH*$_2$-Ph), 4.81 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.85 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 7.08–7.28 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 53.0 (d, C-2), 57.5 (q, O*Me*), 68.2 (t, C-6), 73.5 (t, C*H*$_2$-Ph), 74.9 (d, C-3), 74.9, 76.2 (2t, C*H*$_2$-Ph), 79.5, 81.5 (2d, C-4, C-5), 101.9 (d, *J* = 161.5 Hz, C-1), 109.9 (q, SCN), 127.7, 127.8, 127.9, 128.0, 128.4, 128.5 (m, arom. *C*-H), 137.4, 137.6, 137.9 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2865, 2151, 1496, 1453, 1358, 1048, 736, 696 cm^{-1}.

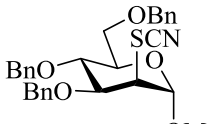
Anal. calcd for $C_{29}H_{31}NO_5S$ (505.62): C 68.89, H 6.18, N 2.77, S 6.34; found: C 68.80, H 6.23, N 2.78, S 6.30.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-mannopyranoside (*α-manno*-4b):

Nature = Colorless viscous oil (0.49 g, 20%).

R_f = 0.44 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +33.9 (c = 1.00 in $CHCl_3$).



α-manno-**4b**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.28 (s, 3 H, O*Me*), 3.58 (dd, *J* = 10.7, 1.9 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.7, 4.0 Hz, 1 H, 6'-H), 3.67 (dd, *J* = 10.7, 8.2 Hz, 1 H, 4-H), 3.70 (ddd, *J* = 10.7, 4.0, 1.9 Hz, 1 H, 5-H), 3.97 (dd, *J* = 4.4, 1.6 Hz, 1 H, 2-H), 4.16 (dd, *J* = 8.2, 4.4 Hz, 1 H, 3-H), 4.37

(d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.42 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 12.0 Hz, 1 H, *CH*$_2$-Ph), 4.68 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.94 (d, *J* = 1.6 Hz, 1 H, 1-H), 7.04–7.31 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 52.2 (d, C-2), 55.3 (q, O*Me*), 68.4 (t, C-6), 71.4 (d, C-4), 71.8, 73.4 (2t, C*H*$_2$-Ph), 73.8 (d, C-5), 75.2 (t, C*H*$_2$-Ph), 77.2 (d, C-3), 99.3 (d, *J* = 172.0 Hz, C-1), 111.8 (q, SCN), 127.6, 127.6, 127.7, 127.9, 128.0, 128.1, 128.3, 128.5 (m, arom *C*-H), 137.0, 137.8, 138.0 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3030, 2912, 2154, 1496, 1453, 1361, 1056, 736, 696 cm^{-1}.

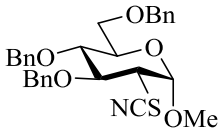
Anal. calcd for $C_{29}H_{31}NO_5S$ (505.62): C 68.89, H 6.18, N 2.77, S 6.34; found: C 68.83, H 5.96, N 2.91, S 6.72.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-glucopyranoside (*α-gluco*-4c):

Nature = Colorless viscous oil (0.17 g, 7%).

R_f = 0.44 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +73.5 (c = 1.00 in $CHCl_3$).



α-gluco-**4c**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.30 (dd, *J* = 10.9, 3.4 Hz, 1 H, 2-H), 3.34 (s, 3 H, O*Me*), 3.59 (dd, *J* = 11.0, 2.0 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.2, 9.0 Hz, 1 H, 4-H), 3.68 (dd, *J* = 11.0, 3.7 Hz, 1 H, 6'-H), 3.74 (ddd, *J* = 10.2, 3.7, 2.0 Hz, 1 H, 5-H), 3.89 (dd, *J* = 10.9, 9.0 Hz, 1 H, 3-H), 4.43 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.44 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.9 Hz, 1 H, *CH*$_2$-Ph), 4.80 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.84 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.85 (d, *J* = 3.4 Hz, 1 H, 1-H), 7.07–7.32 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 52.8 (d, C-2), 55.6 (q, O*Me*), 67.9 (t, C-6), 71.0 (d, C-5), 73.5, 75.0, 76.2 (3t, C*H*$_2$-Ph), 79.2, 80.4 (2d, C-4, C-3), 99.0 (d, *J* = 170.0 Hz, C-1), 111.6 (q, SCN), 127.6, 127.7, 127.8, 127.8, 127.9, 128.0, 128.4, 128.4 (m, arom H), 137.4, 137.6, 137.7 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2907, 2154, 1496, 1453, 1359, 1044, 735, 696 cm^{-1}.

Anal. calcd for $C_{29}H_{31}NO_5S$ (505.62): C 68.89, H 6.18, N 2.77, S 6.34; found: C 68.71, H 7.04, N 2.82, S 6.56.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-mannopyranoside (*β-manno*-4d):

Nature = Colorless viscous oil (0.15 g, 6%).

R_f = 0.21 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = –6.12 (c = 1 in $CHCl_3$).

β-manno-**4d**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.37 (ddd, *J* = 9.5, 3.9, 3.1 Hz, 1 H, 5-H), 3.46 (s, 3 H, O*Me*), 3.61, (dd, *J* = 11.2, 3.9 Hz, 1 H, 6-H), 3.64 (dd, *J* = 11.2, 3.1 Hz, 1 H, 6'-H), 3.71 (t, *J* = 9.5 Hz, 1 H, 4-H), 3.82 (dd, *J* = 9.5, 4.0 Hz, 1 H, 3-H), 4.01 (dd, *J* = 4.0, 1.5 Hz, 1 H, 2-H), 4.42 (d, *J* = 10.4 Hz, 1 H, C*H*$_2$-Ph), 4.43 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.45 (d, *J* = 1.5 Hz, 1 H, 1-H), 4.49 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.53 (d, *J* = 12.1 Hz, 1 H, *CH*$_2$-Ph), 4.77 (d, *J* = 10.4 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 7.07–7.36 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 54.5 (d, C-2), 56.8 (q, O*Me*), 68.5 (t, C-6), 71.8, 73.4 (2t, C*H*$_2$-Ph), 73.8 (d, C-4), 75.1 (t, C*H*$_2$-Ph), 75.9 (d, C-5), 79.7 (d, C-3), 99.4 (d, *J* = 159.9 Hz, C-1), 112.7 (q, SCN), 127.5, 127.6, 127.7, 127.9, 128.0, 128.2, 128.3, 128.4 (m, arom H), 136.9, 137.7, 137.9 (3q, arom. *C*-CH_2O).

IR (Film): *v* = 2865, 2153, 1496, 1453, 1361, 1096, 738, 697 cm^{-1}.

Anal. calcd for $C_{29}H_{31}NO_5S$ (505.62): C 68.89, H 6.18, N 2.77, S 6.34; found: C 68.21, H 6.34, N 3.08, S 6.93.

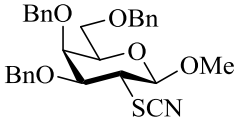
Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-galactopyranoside (*β-galacto*-5a):

Nature = White solid (0.35 g, 14%).

R_f = 0.53 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +60.1 (c = 1.00 in $CHCl_3$).

mp = 72−74 °C.



β-galacto-**5a**

^{1}H NMR (300 MHz, $CDCl_3$): δ = 3.28 (dd, *J* = 11.0, 8.4 Hz, 1 H, 2-H), 3.49 (s, 3 H, O*Me*), 3.52–3.57 (m, 4 H, 3-H, 5-H, 6-H, 6'-H), 3.96 (d, *J* = 2.7 Hz, 1 H, 4-H), 4.33 (d, *J* = 8.4 Hz, 1 H, 1-H), 4.35 (d, *J* = 11.8 Hz, 1 H, C*H*$_2$-Ph), 4.40 (d, *J* = 11.8 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.58 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 4.67 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.77 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 7.17–7.35 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 50.5 (d, C-2), 57.4 (q, O*Me*), 68.2 (t, C-6), 72.3 (d, C-3), 72.9 (t, CH_2-Ph), 73.4 (d, C-4), 73.6, 74.8 (2t, CH_2-Ph), 79.4 (d, C-5), 102.2 (d, *J* = 159.4, C-1), 110.2 (q, SCN), 127.7, 127.8, 127.9, 128.1, 128.2, 128.3, 128.5, 128.6 (m, arom H), 136.9, 137.7, 138.0 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2867, 2150, 1496, 1454, 1357, 1063, 739, 699 cm^{-1}.

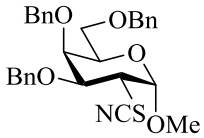
Anal. calcd for $C_{29}H_{31}NO_5S$ (505.62): C 68.89, H 6.18, N 2.77, S 6.34; found: C 68.67, H 6.18, N 2.85, S 6.35.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-galactopyranoside (*a-galacto*-5b):

Nature = Colorless viscous oil (1.35 g, 53%) .

R_f = 0.53 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +11.4 (c = 1.00 in $CHCl_3$).



α-galacto-**5b**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.28 (s, 3 H, O*Me*), 3.47 (dd, *J* = 9.4, 6.0 Hz, 1 H, 6-H), 3.49 (dd, *J* = 9.4, 7.1 Hz, 1 H, 6'-H), 3.75–3.76 (m, 2 H, 2-H, 3-H), 3.82 (dd, *J* = 7.1, 4.9 Hz, 1 H, 5-H), 4.06 (dd, *J* = 4.9, 3.0 Hz, 1 H, 4-H), 4.30 (d, *J* = 11.7 Hz, 1 H, CH_2-Ph), 4.39 (d, *J* = 11.7 Hz, 1 H, CH_2-Ph), 4.41 (d, *J* = 11.6 Hz, 1 H, CH_2-Ph), 4.48 (d, *J* = 11.7 Hz, 1 H, *CH*$_2$-Ph), 4.67 (d, *J* = 11.7 Hz, 1 H, CH_2-Ph), 4.82 (d, *J* = 11.6 Hz, 1 H, CH_2-Ph), 4.99 (s, 1 H, 1-H), 7.15–7.32 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 50.9 (d, C-2), 55.4 (q, O*Me*), 68.6 (t, C-6), 69.7 (d, C-5), 70.5 (t, CH_2-Ph), 73.2 (d, C-4), 73.5 (t, CH_2-Ph), 73.7 (d, C-3), 74.9 (t, CH_2-Ph), 101.2 (d, *J* = 173.6 Hz, C-1), 115.1 (q, SCN), 127.5, 127.7, 127.7, 128.0, 128.2, 128.3, 128.4, 128.6 (m, arom H), 137.1, 137.7, 137.8 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2917, 2150, 1496, 1453, 1348, 1050, 732, 695 cm^{-1}.

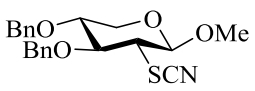
Anal. calcd for $C_{29}H_{31}NO_5S$ (505.62): C 68.89, H 6.18, N 2.77, S 6.34; found: C 68.86, H 6.08, N 2.83, S 6.56.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-xylopyranoside (*β-xylo*-6a):

Nature = Colorless viscous liquid (1.20 g, 63%).

R_f = 0.55 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +74.7 (c = 1.00 in $CHCl_3$).



β-xylo-**6a**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.78 (dd, *J* = 10.0, 8.2 Hz, 1 H, 2-H), 3.19 (dd, *J* = 11.8, 10.0 Hz, 1 H, 3-H), 3.47 (s, 3 H, O*Me*), 3.55–3.62 (m, 2 H, 4-H, 5' H), 3.93 (dd, *J* = 11.6, 4.7 Hz, 1 H, 5-H), 4.31 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.55 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.62 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.77 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.88 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 7.23–7.29 (m, 10 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 52.5 (d, C-2), 57.3 (q, O*Me*), 63.3 (t, C-5), 73.2, 75.9 (2t, C*H*$_2$-Ph), 79.1, 80.0 (2d, C-4, C-3), 102.5 (d, *J* = 163.4 Hz, C-1), 110.1 (q, SCN), 127.8, 128.0, 128.1, 128.1, 128.4, 128.5 (m, arom H), 137.5, 137.6 (2q, arom. *C*-CH_2O).

IR (film): *v* = 2866, 2152, 1497, 1454, 1373, 1077, 738, 696 cm^{-1}.

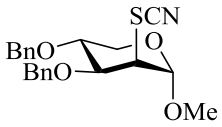
Anal. calcd for $C_{21}H_{23}NO_4S$ (385.47): C 65.43, H 6.01, N 3.63, S 8.32; found: C 65.46, H 5.74, N 3.72, S 8.34.

Methyl 3,4-di-O-benzyl-2-deoxy-2-thiocyanato-α-D-lyxopyranoside (*α-lyxo*-6b):

Nature = Colorless viscous liquid (0.30 g, 16%).

R_f = 0.51 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +28.4 (c = 0.54 in $CHCl_3$).



α-lyxo-**6b**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.39 (s, 3 H, O*Me*), 3.46 (td, *J* = 5.3, 3.0 Hz, 1 H, 4-H), 3.71 (dd, *J* = 12.0, 3.0 Hz, 1 H, 5'-H), 3.73 (dd, *J* = 6.0, 3.7 Hz, 1 H, 2-H), 3.76 (dd, *J* = 12.0, 5.3 Hz, 1 H, 5-H), 3.95 (dd, *J* = 5.3, 3.7 Hz, 1 H, 3-H), 4.47 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.55 (dd, *J* = 11.7 Hz, 2 H, C*H*$_2$-Ph), 4.64 (d, *J* = 6.0 Hz, 1 H, 1-H), 7.16–7.29 (m, 10 H, arom H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 51.3 (d, C-2), 56.3 (q, O*Me*), 62.1 (t, C-5), 72.0 (t, C*H*$_2$-Ph), 72.5 (d, C-4), 72.9 (t, C*H*$_2$-Ph), 76.8 (d, C-3), 100.3 (d, *J* = 168.1 Hz, C-1), 111.8 (q, SCN), 127.7, 127.9, 128.0, 128.2, 128.5, 128.5 (m, arom H), 136.8, 137.5 (2q, arom. *C*-CH_2O).

IR (film): v = 2162, 1967, 1452, 1357, 1081, 733, 693 cm^{-1}.

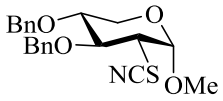
Anal. calcd for $C_{21}H_{23}NO_4S$ (385.47): C 65.43, H 6.01, N 3.63, S 8.32; found: C 65.09, H 6.06, N 3.73, S 8.87.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-xylopyranoside (*α-xylo*-6c):

Nature = Colorless viscous liquid (0.065 g, 3%).

R_f = 0.48 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = –41.9 (c = 0.50 in $CHCl_3$).



α-xylo-**6c**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.35 (ddd, J = 4.1, 3.1, 1.8 Hz, 1 H, 4-H), 3.36 (s, 3 H, O*Me*), 3.45 (dd, J = 12.4, 3.1 Hz, 1 H, 5-H), 3.72 (t, J = 4.1 Hz, 1 H, 3-H), 3.86 (t, J = 4.1 Hz, 1 H, 2-H), 3.93 (dd, J = 12.4, 1.8 Hz, 1 H, 5'-H), 4.40 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.45 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.51 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.57 (d, J = 12.1 Hz, 1 H, CH_2-Ph), 4.66 (d, J = 4.1 Hz, 1 H, 1-H), 7.17–7.29 (m, 10 H, arom H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 50.2 (d, C-2), 56.5 (q, O*Me*), 57.1 (t, C-5), 71.4 (t, CH_2-Ph), 72.4 (d, C-4), 73.3 (t, CH_2-Ph), 74.1 (d, C-3), 97.8 (d, J = 169.3 Hz, C-1), 112.3 (q, SCN), 127.7, 128.0, 128.1, 128.5, 128.5 (m, arom H), 136.9, 137.3 (2q, arom. *C*-CH_2O).

IR (film): v = 2927, 2152, 1496, 1454, 1352, 1092, 736, 697 cm^{-1}.

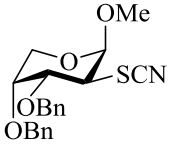
Anal. calcd for $C_{21}H_{23}NO_4S$ (385.47): C 65.43, H 6.01, N 3.63, S 8.32; found: C 65.52, H 6.23, N 3.76, S 8.46.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-arabinopyranoside (*β-arabino*-7a):

Nature = Colorless viscous oil (1.38 g, 72%).

R_f = 0.43 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = –65.3 (c = 1.00 in $CHCl_3$).



β-arabino-**7a**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.33 (s, 3 H, O*Me*), 3.56 (t, J = 3.8 Hz, 1 H, 2-H), 3.59 (td, J = 5.0, 2.6 Hz, 1 H, 4-H), 3.67 (dd, J = 12.0, 2.6 Hz, 1 H, 5-H), 3.72 (dd, J = 12.0, 5.0 Hz, 1 H, 5'-H), 4.08 (dd, J = 3.8, 2.6 Hz, 1 H, 3-H), 4.59 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.60 (d, J = 11.3 Hz,

1 H, C*H*$_2$-Ph), 4.61 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 12.0 Hz, 1 H, *CH*$_2$-Ph), 4.82 (d, *J* = 3.8 Hz, 1 H, 1-H), 7.20–7.29 (m, 10 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 51.9 (d, C-2), 56.1 (q, O*Me*), 61.6 (t, C-5), 72.1, 72.3 (2t, C*H*$_2$-Ph), 73.2, 74.1 (2d, C-3, C-4), 101.3 (d, *J* = 171.1 Hz, C-1), 113.9 (q, SCN), 127.7, 127.7, 127.8, 128.0, 128.4, 128.4 (m, arom H), 137.3, 137.5 (2q, arom. *C*-CH_2O).

IR (film): *v* = 2874, 2151, 1497, 1453, 1346, 1054, 735, 695 cm^{-1}.

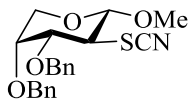
Anal. calcd for $C_{21}H_{23}NO_4S$ (385.47): C 65.43, H 6.01, N 3.63, S 8.32; found: C 65.21, H 6.09, N 3.61, S 8.33.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-arabinopyranoside (*α-arabino*-7b):

Nature = Colorless viscous oil (0.40 g, 21%).

R_f = 0.30 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = –122.2 (c = 1.00 in $CHCl_3$).



α-arabino-**7b**

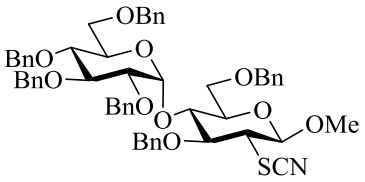
^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.27 (dd, *J* = 13.0, 0.7 Hz, 1 H, 5'-H), 3.30 (dd, *J* = 10.9, 8.6 Hz, 1 H, 2-H), 3.50 (s, 3 H, O*Me*), 3.51 (dd, *J* = 10.9, 2.9 Hz, 1 H, 3-H), 3.69 (t, *J* = 2.9 Hz, 1 H, 4-H), 4.07 (dd, *J* = 13.0, 2.9 Hz, 1 H, 5-H), 4.25, (d, *J* = 8.6 Hz, 1 H, 1-H), 4.48 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.67 (d, *J* = 12.2 Hz, 1 H, *CH*$_2$-Ph), 7.20–7.28 (m, 10 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 50.3 (d, C-2), 57.3 (q, O*Me*), 63.3 (t, C-5), 71.1 (d, C-4), 71.4, 72.2 (2t, C*H*$_2$-Ph), 77.7 (d, C-3), 102.5 (d, *J* = 160.3 Hz, C-1), 110.2 (q, SCN), 127.8, 127.9, 128.1, 128.1, 128.4, 128.5 (m, arom H), 136.9, 137.6 (2q, arom. *C*-CH_2O).

IR (film): *v* = 2867, 2151, 1496, 1454, 1352, 1056, 742, 699 cm^{-1}.

Anal. calcd for $C_{21}H_{23}NO_4S$ (385.47): C 65.43, H 6.01, N 3.63, S 8.32; found: C 65.44, H 6.35, N 3.69, S 8.25.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-maltopyranoside (*β-malto*-8a):



β-malto-**8a**

Nature = Colorless viscous liquid (2.12 g, 45%).

R_f = 0.50 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +58.1 (c = 1.00 in $CHCl_3$).

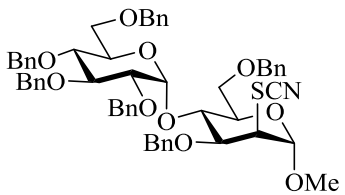
^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.92 (dd, *J* = 10.9, 8.3 Hz, 1 H, 2-H), 3.40 (dd, *J* = 10.8, 2.2 Hz, 1 H, 6-H), 3.44 (dd, *J* = 9.8, 3.4 Hz, 1 H, 8-H), 3.47 (ddd, *J* = 9.4, 3.8, 2.2 Hz, 1 H, 5-H), 3.50 (dd, *J* = 10.8, 3.8 Hz, 1 H, 6'-H), 3.51 (s, 3 H, O*Me*), 3.55 (dd, *J* = 10.0, 8.8 Hz, 1 H, 10-H), 3.67 (dd, *J* = 11.3, 2.3 Hz, 1 H, 12-H), 3.75 (ddd, *J* = 10.0, 3.8, 2.3 Hz, 1 H, 11-H), 3.79 (dd, *J* = 10.9, 8.2 Hz, 1 H, 3-H), 3.86 (dd, *J* = 9.8, 8.8 Hz, 1 H, 9-H), 3.88 (dd, *J* = 11.3, 3.8 Hz, 1 H, 12'-H), 4.04 (dd, *J* = 9.4, 8.2 Hz, 1 H, 4-H), 4.28 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.37 (d, *J* = 8.3 Hz, 1 H, 1-H), 4.39 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.43 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.44 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.80 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 5.01 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 5.30 (d, *J* = 3.4 Hz, 1 H, 7-H), 7.06–7.20 (m, 30 H, arom H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 52.7 (d, C-2), 57.3 (q, O*Me*), 68.3, 68.4 (2t, C-6, C-12), 71.2 (d, C-11), 73.2, 73.3, 73.5, 74.1 (4t, C*H*$_2$-Ph), 74.8 (d, C-5), 75.0, 75.6 (2t, C*H*$_2$-Ph), 75.6, 77.6, 79.4, 81.5, 81.9 (5d, C-4, C-10, C-8, C-3, C-9), 97.6 (d, C-7), 101.7 (d, *J* = 162.1 Hz, C-1), 110.0 (q, SCN), 127.4, 127.5, 127.6, 127.6, 127.7, 127.8, 127.9, 128.2, 128.3, 128.3, 128.3, 128.4 (m, arom. *C*-H), 137.5, 137.7, 137.8, 138.0, 138.2, 138.5 (6q, arom. *C*-CH_2O).

IR (film): *v* = 2866, 2149, 1496, 1453, 1361, 1044, 1026, 732, 694 cm^{-1}.

Anal. calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C 71.70, H 6.34, N 1.49, S 3.42; found: C 71.42, H 6.18, N 1.74, S 3.58.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-epi-2-thiocyanato-*α*-D-maltopyranoside (*α-epi-malto*-8b):



α-epi-malto-**8b**

Nature = Colorless viscous liquid (0.806 g, 17%).

R_f = 0.38 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +61.4 (c = 1.00 in $CHCl_3$).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.27 (dd, *J* = 10.7, 1.6 Hz, 1 H, 12-H), 3.34 (s, 3 H, O*Me*), 3.40 (dd, *J* = 9.8, 3.8 Hz, 1 H, 8-H), 3.44 (dd, *J* = 10.7, 2.6 Hz, 1 H, 12'-H), 3.54 (dd, *J* = 9.8, 8.4 Hz, 1 H, 9-H), 3.56–3.59 (m, 1 H, 11-H), 3.60 (dd, *J* = 11.3, 2.2 Hz, 1 H, 6'-H), 3.76 (dd, *J* = 9.7, 8.4 Hz, 1 H, 10-H), 3.77 (dd, *J* = 11.3, 4.5 Hz, 1 H, 6-H), 3.85 (ddd, *J* = 9.1, 4.5, 2.2 Hz, 1 H, 5-H), 3.95 (dd, *J* = 4.5, 2.2 Hz, 1 H, 2-H), 4.07 (dd, *J* = 9.1, 8.2 Hz, 1 H, 4-H), 4.17 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.23 (dd, *J* = 8.2, 4.5 Hz, 1 H, 3-H), 4.31 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.35 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.42–4.45 (m, 4 H, C*H*$_2$-Ph), 4.52 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.59 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.68 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.82 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.94 (d, *J* = 2.2 Hz, 1 H, 1-H), 5.43 (d, *J* = 3.8 Hz, 1 H, 7-H), 6.99–7.23 (m, 30 H, arom H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 51.3 (d, C-2), 55.5 (q, O*Me*), 67.9, 68.8 (2t, C-12, C-6), 69.5, 71.1 (2d, C-4, C-5), 71.1 (t, C*H*$_2$-Ph), 71.2 (d, C-10), 72.9, 73.4, 73.4, 75.0, 75.5 (5t, C*H*$_2$-Ph), 77.4, 77.9, 79.3, 81.7 (4d, C-9, C-3, C-8, C-11), 96.9 (d, C-7), 99.2 (d, *J* = 172.8 Hz, C-1), 111.6 (q, SCN), 127.3, 127.5, 127.6, 127.6, 127.7, 127.7, 127.8, 127.9, 128.0, 128.2, 128.3, 128.3, 128.5 (m, arom. *C*-H), 136.6, 137.8, 137.9, 138.2, 138.3, 138.7 (6q, arom. *C*-CH_2O).

IR (Film): *v* = 2864, 2153, 1497, 1454, 1361, 1054, 738, 694 cm^{-1}.

Anal. calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C 71.70, H 6.34, N 1.49, S 3.42; found: C 72.18, H 6.35, N 1.72, S 3.55.

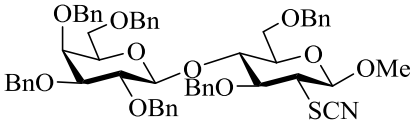
Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thiocyanato-*β*-D-lactopyranoside (*β-lacto*-9a):

Nature = White solid (2.34 g, 50%).

R_f = 0.50 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +40.8 (c = 0.97 in $CHCl_3$).

m.p. = 45–46 °C.



β-lacto-**9a**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.78 (dd, *J* = 10.9, 8.3 Hz, 1 H, 2-H), 3.23–3.26 (m, 1 H, H-11), 3.28 (ddd, *J* = 9.8, 3.7, 1.9 Hz, 1 H, 5-H), 3.30 (dd, *J* = 9.8, 3.0 Hz, 1 H, 12-H), 3.32 (dd, *J* = 7.5, 3.0 Hz, 1 H, 9-H), 3.42 (dd, *J* = 9.8, 4.9 Hz, 1 H, 12'-H), 3.49 (s, 3 H, O*Me*), 3.52 (dd, *J* = 10.9, 8.6 Hz, 1 H, 3-H), 3.59 (dd, *J* = 10.9, 1.9 Hz, 1 H, 6-H), 3.70 (dd, *J* = 9.8, 7.5 Hz, 1 H, 8-H), 3.76

(dd, *J* = 10.9, 3.7 Hz, 1 H, 6'-H), 3.83 (d, *J* = 3.0 Hz, 1 H, 10-H), 3.96 (dd, *J* = 9.8, 8.6 Hz, 1 H, 4-H), 4.12 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.24 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.29 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.32 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.33 (d, *J* = 8.3 Hz, 1 H, 1-H), 4.46 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.61 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.65 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.70 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.76 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.90 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 5.10 (d, *J* = 9.8 Hz, 1 H, 7-H), 7.04–7.28 (m, 30 H, arom H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 52.8 (d, C-2), 57.4 (q, O*Me*), 67.3, 67.9 (2t, C-6, C-12), 72.5, 73.0 (2t, C*H*$_2$-Ph), 73.0 (d, C-10), 73.3 (d, C-11), 73.5, 74.7 (2t, C*H*$_2$-Ph), 74.9 (d, C-5), 75.3, 75.9 (2t, C*H*$_2$-Ph), 77.2, 79.5, 79.8, 82.3 (4d, C-4, C-3, C-8, C-9), 101.9 (d, C-7), 102.5 (d, *J* = 162.1 Hz, C-1), 110.2 (q, SCN), 127.3, 127.3, 127.5, 127.5, 127.6, 127.7, 127.7, 127.8, 128.0, 128.1, 128.2, 128.3, 128.4 (m, arom. *C*-H), 137.9, 137.9, 137.9, 138.3, 138.6, 138.8 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3030, 2871, 2152, 1496, 1453, 1362, 1092, 1061, 733, 695 cm^{-1}.

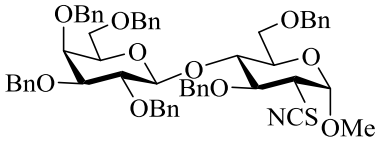
Anal. calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C 71.70, H 6.34, N 1.49, S 3.42; found: C 72.15, H 6.00, N 1.51, S 3.46.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thiocyanato-*α*-D-lactopyranoside (*α-lacto*-9b).

Nature = Colorless viscous liquid (0.369 g, 8%).

R_f = 0.42 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +41.2 (c = 1.03 in $CHCl_3$).



α-lacto-**9b**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.20 (dd, *J* = 11.0, 3.5 Hz, 1 H, 2-H), 3.20–3.25 (m, 2 H, H-6, H-11), 3.27 (dd, *J* = 9.8, 3.2 Hz, 1 H, 9-H), 3.35 (s, 3 H, O*Me*), 3.38 (dd, *J* = 12.5, 2.3 Hz, 1 H, 6'-H), 3.45 (dd, *J* = 11.0, 1.9 Hz, 1 H, 12'-H), 3.59 (dt, *J* = 10.1, 2.3 Hz, 1 H, 5-H), 3.69 (dd, *J* = 9.8, 7.6 Hz, 1 H, 8-H), 3.73 (dd, *J* = 11.0, 8.8 Hz, 1 H, 3-H), 3.79 (dd, *J* = 11.0, 3.2 Hz, 1 H, 12-H), 3.82 (d, *J* = 3.2 Hz, 1 H, 10-H), 3.92 (dd, *J* = 10.1, 8.8 Hz, 1 H, 4-H), 4.11 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.22 (d, *J* = 7.6 Hz, 1 H, 7-H), 4.24 (d, *J* = 11.9 Hz, 1 H, C*H*$_2$-Ph), 4.28 (d, *J* = 11.9 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.61 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.64 (d, *J* = 12.0 Hz, 1 H,

C*H*$_2$-Ph), 4.70 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.76 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.79 (d, *J* = 3.5 Hz, 1 H, 1-H), 4.89 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 5.06 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 7.05–7.31 (m, 30 H, arom H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 52.0 (d, C-2), 55.7 (q, O*Me*), 67.4, 68.0 (2t, C-6, C-12), 71.0 (d, C-5), 72.5, 73.2 (2d, C*H*$_2$-Ph), 73.2 (d, C-11), 73.3 (d, C*H*$_2$-Ph), 73.6 (d, C-10), 74.7, 75.3, 75.7 (3d, C*H*$_2$-Ph), 77.3, 77.9, 79.9, 82.3 (4d, C-4, C-3, C-8, C-9), 98.9 (d, *J* = 169.7 Hz, C-1), 102.7 (d, C-7), 111.4 (q, SCN), 127.3, 127.4, 127.4, 127.5, 127.6, 127.6, 127.7, 127.7, 127.7, 127.8, 127.9, 128.1, 128.3, 128.5 (m, arom. *C*-H), 137.8, 138.1, 138.1, 138.4, 138.7, 138.9 (6q, arom. *C*-CH_2O).

IR (film): *v* = 2867, 2156, 1496, 1453, 1362, 1097, 731, 693 cm^{-1}.

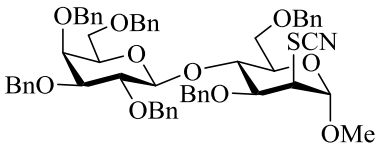
Anal. calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C 71.70, H 6.34, N 1.49, S 3.42; found: C 71.61, H 6.25, N 1.86, S 4.42.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-epi-2-thiocyanato-*α*-D-lactopyranoside (*α-epi-lacto*-9c):

Nature = Colorless viscous liquid (0.742 g, 16%).

R_f = 0.50 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +7.8 (c = 0.99 in $CHCl_3$).



α-epi-lacto-**9c**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.27–3.31 (m, 1 H, H-5), 3.31 (dd, *J* = 11.9, 1.9 Hz, 1 H, 6-H), 3.32 (s, 3 H, O*Me*), 3.37 (dd, *J* = 9.4, 5.6 Hz, 1 H, 9-H), 3.41 (dd, *J* = 9.8, 7.1 Hz, 1 H, 12-H), 3.53 (dd, *J* = 11.9, 3.8 Hz, 1 H, 6'-H), 3.65 (dd, *J* = 9.4, 7.5 Hz, 1 H, 8-H), 3.68 (dd, *J* = 9.8, 4.9 Hz, 1 H, 12'-H), 3.67–3.70 (m, 1 H, 11-H), 3.77 (d, *J* = 2.9 Hz, 1 H, 10-H), 3.82 (dd, *J* = 4.5, 3.0 Hz, 1 H, 2-H), 3.89 (dd, *J* = 8.2, 7.2 Hz, 1 H, 4-H), 4.07 (dd, *J* = 7.2, 4.5 Hz, 1 H, 3-H), 4.18 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.26 (d, *J* = 7.5 Hz, 1 H, 7-H), 4.30 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.30 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.59 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.65 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.70 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.86 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.89 (d, *J* = 3.0 Hz, 1 H, 1-H), 7.13–7.26 (m, 30 H, arom H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 52.0 (d, C-2), 55.6 (q, O*Me*), 68.2, 68.7 (2t, C-6, C-12), 71.7 (d, C-10), 72.4, 72.7, 73.2, 73.4 (4t, CH_2-Ph), 73.5, 73.5, 74.3 (3d, C-11, C-5, C-4), 74.6, 75.2 (2t, CH_2-Ph), 76.2, 79.6, 82.4 (3d, C-3, C-8, C-9), 99.5 (d, C-7), 103.5 (d, *J* = 173.0 Hz, C-1), 111.9 (q, SCN), 127.5, 127.5, 127.5, 127.6, 127.7, 127.8, 127.8, 128.0, 128.2, 128.3, 128.4 (m, arom. *C*-H), 137.8, 137.9, 138.2, 138.3, 138.6, 138.6 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3063, 2864, 2009, 1496, 1453, 1362, 1062, 1026, 732, 695 cm^{-1}.

Anal. calcd for $C_{56}H_{59}NO_{10}S$ (938.13): C 71.70, H 6.34, N 1.49, S 3.42; found: C 71.50, H 6.06, N 1.60, S 3.72.

General procedure for the lithium aluminium hydride reduction of 2-thiocyanates (4a–9a) to 2-thiols (16–23).

A solution of appropriate 2-thiocyanate **4a**–**9a** (0.5 mmol) in dry tetrahedrofuran (15 mL) was cooled to 0 °C under nitrogen atmosphere. At this temperature, lithium aluminium hydride (48 mg, 1.25 mmol, 2.5 equiv) was added and the solution was stirred for 30 min. Upon completion, the reaction mixture was slowly quenched with ice and filtered through a pad of celite. The solvent was removed under reduced pressure and the resulting residue was extracted with dichloromethane (3 x 20 mL) and water (20 mL). The combined organic extracts were dried over sodium sulfate, concentrated and purified by silica gel column chromatography (hexane/MTBE 85:15) to afford the 2-thiols **16**–**23**. *Caution! Due to the liberation of highly toxic HCN, the reaction and workup has to be carried out in a fume under careful handling.*

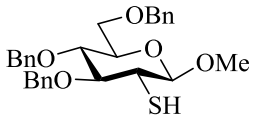
Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*β*-D-glucopyranoside(*β-gluco*-16).

Nature = White solid (200 mg, 83%).

R_f = 0.53 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +17.7 (c = 1.00 in $CHCl_3$).

m.p. = 45–46 °C.



β-gluco-**16**

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.92 (d, *J* = 3.2 Hz, 1 H, S*H*), 2.97 (ddd, *J* = 10.6, 8.5, 3.2 Hz, 1 H, 2-H), 3.35 (dd, *J* = 10.6, 8.7 Hz, 1 H, 3-H), 3.38 (ddd, *J* = 9.4, 3.8, 1.7 Hz, 1 H, 5-H), 3.42 (s, 3 H, O*Me*), 3.54 (dd, *J* = 9.4, 8.7 Hz, 1 H, 4-H), 3.68 (dd, *J* = 10.7, 1.7 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.7, 3.8 Hz, 1 H, 6'-H), 4.09 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.43 (d, *J* = 12.2 Hz, 1 H, CH_2-Ph),

4.45 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 10.8 Hz, 1 H, *CH*$_2$-Ph), 4.71 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.76 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 7.06–7.29 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 46.1 (d, C-2), 57.0 (q, O*Me*), 68.7 (t, C-6), 73.5, 74.8 (2t, C*H*$_2$-Ph), 75.2 (d, C-3), 75.4 (t, C*H*$_2$-Ph), 79.0, 84.8 (2d, C-4, C-5), 104.7 (d, C-1), 127.6, 127.7, 127.8, 127.8, 128.0, 128.4 (m, arom C-H), 137.9, 137.9, 138.0 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2862, 1496, 1453, 1359, 1046, 735, 696 cm^{-1}.

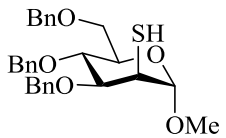
Anal. calcd for $C_{28}H_{32}O_5S$ (480.61): C 69.97, H 6.71, S 6.67; found: C 70.16, H 6.45, S 6.60.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*α*-D-mannopyranoside (*α-manno*-17):

Nature = Colorless viscous liquid (204 mg, 85%).

R_f = 0.51 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +38.5 (c = 0.98 in $CHCl_3$).



α-manno-**17**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.77 (d, *J* = 7.9 Hz, 1 H, S*H*), 3.24 (s, 3 H, O*Me*), 3.41 (ddd, *J* = 7.9, 4.5, 1.5 Hz, 1 H, 2-H), 3.61 (dd, *J* = 12.4, 3.8 Hz, 1 H, 6-H), 3.65–3.68 (m, 1 H, 5-H), 3.68 (dd, *J* = 12.4, 3.4 Hz, 1 H, 6'-H), 3.87 (dd, *J* = 9.5, 9.0 Hz, 1 H, 4-H), 4.01 (dd, *J* = 9.0, 4.5 Hz, 1 H, 3-H), 4.38 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.43 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.57 (d, *J* = 11.5 Hz, 1 H, *CH*$_2$-Ph), 4.58 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 1.5 Hz, 1 H, 1-H), 4.77 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 7.07–7.30 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 42.5 (d, C-2), 54.9 (q, O*Me*), 68.9 (t, C-6), 71.3 (t, C*H*$_2$-Ph), 71.3 (d, C-5), 73.3 (t, C*H*$_2$-Ph), 73.9 (d, C-4), 74.9 (t, C*H*$_2$-Ph), 78.3 (d, C-3), 101.1 (d, C-1), 127.4, 127.5, 127.6, 127.7, 127.8, 127.8, 128.2, 128.3 (m, arom C-H), 138.0, 138.2, 138.3 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2906, 2067, 1496, 1452, 1360, 1053, 733, 695 cm^{-1}.

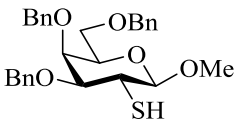
Anal. calcd for $C_{28}H_{32}O_5S$ (480.61): C 69.97, H 6.71, S 6.67; found: C 70.14, H 6.87, S 6.72.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*β*-D-galactopyranoside (*β-galacto*-18):

Nature = White solid (206 mg, 86%).

R_f = 0.55 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +8.8 (c = 0.97 in $CHCl_3$).



β-galacto-**18**

m.p. = 106–107 °C.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.97 (d, *J* = 2.5 Hz, 1 H, S*H*), 3.26 (dd, *J* = 11.1, 2.5 Hz, 1 H, 3-H), 2.42 (ddd, *J* = 11.1, 8.5, 2.5 Hz, 1 H, 2-H), 3.43 (s, 3 H, O*Me*), 3.51 (ddd, *J* = 7.3, 5.0, 1.0 Hz, 1 H, 5-H), 3.55 (dd, *J* = 8.8, 5.0 Hz, 1 H, 6-H), 3.58 (dd, *J* = 8.8, 7.3 Hz, 1 H, 6'-H), 3.85 (dd, *J* = 2.5, 1.0 Hz, 1 H, 4-H), 4.09 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.37 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.41 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.45 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 11.7 Hz, 1 H, *CH*$_2$-Ph), 4.64 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.79 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 7.15–7.32 (m, 15 H, arom H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 42.8 (d, C-2), 56.9 (q, O*Me*), 68.7 (t, C-6), 71.2 (d, C-4), 72.1, 73.6 (2t, C*H*$_2$-Ph), 73.7 (d, C-5), 74.3 (t, C*H*$_2$-Ph), 82.7 (d, C-3), 105.0 (d, C-1), 127.6, 127.8, 127.9, 128.0, 128.1, 128.2, 128.4, 128.5 (m, arom C-H), 137.3, 137.8, 138.3 (3q, arom. *C*-CH_2O).

IR (Film): *v* = 2914, 2857, 1988, 1453, 1362, 1060, 744, 697 cm^{-1}.

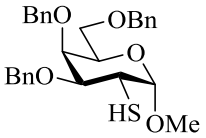
Anal. calcd for $C_{28}H_{32}O_5S$ (480): C 69.97, H 6.71, S 6.67; found: C 70.07, H 6.50, S 7.17.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*α*-D-galactopyranoside (*α-galacto*-19):

Nature = Colorless viscous liquid (207 mg, 86%).

R_f = 0.55 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +2.7 (c = 0.97 in $CHCl_3$).



α-galacto-**19**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.93 (d, *J* = 11.1 Hz, 1 H, S*H*), 3.28 (ddd, *J* = 11.1, 6.4, 1.2 Hz, 1 H, 2-H), 3.99 (s, 3 H, O*Me*), 3.72–3.73 (m, 2 H, 6-H, 6'-H), 3.92–3.93 (m, 1 H, 5-H), 4.02 (dd, *J* = 3.9, 1.7 Hz, 1 H, 4-H), 4.04 (dd, *J* = 6.4, 1.7 Hz, 1 H, 3-H), 4.50 (d, *J* = 11.8 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.59 (d, *J* = 11.8 Hz, 1 H, C*H*$_2$-Ph), 4.62 (d, *J* = 11.5 Hz, 1 H, *CH*$_2$-Ph), 4.83 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 5.03 (d, *J* = 1.2 Hz, 1 H, 1-H), 5.11 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 7.28–7.49 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 40.2 (d, C-2), 55.1 (q, O*Me*), 69.3 (t, C-6), 69.8 (d, C-4), 70.0, 73.5 (2t, CH_2-Ph), 73.9, 74.3 (2d, C-3, C-5), 75.0 (t, CH_2-Ph), 104.7 (d, C-1), 127.4, 127.6, 127.6, 127.6, 128.0, 128.1, 128.3, 128.3 (m, arom C-H), 138.1, 138.1, 138.6 (3q, arom. *C*-CH_2O).

IR (film): ν = 2909, 1452, 1353, 1109, 1148, 951, 732, 695 cm^{-1}.

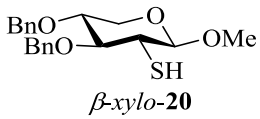
Anal. calcd for $C_{28}H_{32}O_5S$ (480.61): C 69.97, H 6.71, S 6.67; found: C 69.91, H 6.80, S 6.90.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-*β*-D-xylopyranoside (*β-xylo*-20):

Nature = Colorless viscous liquid (147 mg, 82%).

R_f = 0.57 (hexane/ethyl acetate 7:3).

$[\alpha]_D^{20}$ = +6.7 (c = 1.01 in $CHCl_3$).



β-xylo-**20**

^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.99 (d, *J* = 3.5 Hz, 1 H, S*H*), 2.88 (ddd, *J* = 10.3, 8.2, 3.5 Hz, 1 H, 2-H), 3.17 (dd, *J* = 11.6, 9.9 Hz, 1 H, 5-H), 3.32 (dd, *J* = 10.3, 8.4 Hz, 1 H, 3-H), 3.41 (s, 3 H, O*Me*), 3.53 (ddd, *J* = 9.9, 8.4, 5.1 Hz, 1 H, 4-H), 3.94 (dd, *J* = 11.6, 5.1 Hz, 1 H, 5'-H), 4.08 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.53 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 4.62 (d, *J* = 11.5 Hz, 1 H, CH_2-Ph), 4.69 (d, *J* = 10.8 Hz, 1 H, CH_2-Ph), 4.84 (d, *J* = 10.8 Hz, 1 H, *CH*$_2$-Ph), 7.16–7.33 (m, 10 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 45.5 (d, C-2), 56.9 (q, O*Me*), 63.8 (t, C-5), 73.1, 75.3 (2t, CH_2-Ph), 78.8, 83.4 (2d, C-3, C-4), 105.3 (d, C-1), 127.8, 127.9, 128.1, 128.4, 128.5 (m, arom C-H), 137.9, 138.0 (2q, arom. *C*-CH_2O).

IR (film): ν = 2857, 1725, 1496, 1453, 1371, 1057, 736, 696 cm^{-1}.

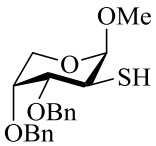
Anal. calcd for $C_{20}H_{24}O_4S$ (360.46): C 66.64, H 6.71, S 8.90; found: C 66.83, H 6.46, S 8.78.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-*β*-D-arabinopyranoside (*β-arabino*-21):

Nature = Colorless viscous liquid (150 mg, 83%).

R_f = 0.45 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = –30.5 (c = 1.00 in $CHCl_3$).



β-arabino-**21**

^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.11 (d, *J* = 9.3 Hz, 1 H, S*H*), 2.76 (ddd, *J* = 9.3, 7.4, 3.1 Hz, 1 H, 2-H), 3.43 (s, 3 H, O*Me*), 3.57 (ddd, *J* = 8.2, 5.2, 3.1 Hz, 1 H, 4-H), 3.76 (dd, *J* = 11.0, 5.2 Hz,

1 H, 5-H), 3.78 (dd, *J* = 11.0, 8.2 Hz, 1 H, 5'-H), 3.95 (t, *J* = 3.1 Hz, 1 H, 3-H), 4.40 (d, *J* = 7.4 Hz, 1 H, 1-H), 4.53 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.58 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.59 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.84 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 7.13–7.34 (m, 10 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 44.0 (d, C-2), 56.7 (q, O*Me*), 62.1 (t, C-5), 71.7, 74.4 (2t, C*H*$_2$-Ph), 76.4, 77.0 (2d, C-3, C-4), 103.6 (d, C-1), 127.4, 127.6, 127.7, 127.8, 128.2, 128.4 (m, arom C-H), 137.9, 138.3 (2q, arom. *C*-CH_2O).

IR (film): *v* = 2871, 2572, 1496, 1453, 1372, 1057, 736, 696 cm^{-1}.

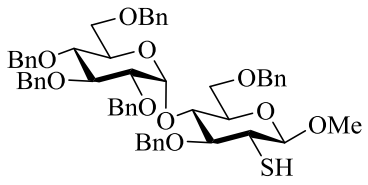
Anal. calcd for $C_{20}H_{24}O_4S$ (360.46): C 66.64, H 6.71, S 8.90; found:: C 66.62, H 6.62, S 9.15.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thio-*β*-D-maltopyranoside (*β-malto*-22):

Nature = Colorless viscous liquid (383 mg, 84%).

R_f = 0.52 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +33.6 (c = 0.96 in $CHCl_3$).



β-malto-**22**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.02 (d, *J* = 3.5 Hz, 1 H, S*H*), 3.10 (ddd, *J* = 10.4, 8.2, 3.5 Hz, 1 H, 2-H), 3.38 (dd, *J* = 10.6, 2.1 Hz, 1 H, 12-H), 3.42 (dd, *J* = 9.7, 3.5 Hz, 1 H, 8-H), 3.46 (s, 3 H, O*Me*), 3.49 (dd, *J* = 10.6, 3.3 Hz, 1 H, 12'-H), 3.50 (ddd, *J* = 9.2, 4.1, 2.2 Hz, 1 H, 5-H), 3.55 (dd, *J* = 10.1, 9.1 Hz, 1 H, 10-H), 3.62 (dd, *J* = 10.4, 8.5 Hz, 1 H, 3-H), 3.69 (dd, *J* = 11.0, 2.2 Hz, 1 H, 6-H), 3.72 (ddd, *J* = 10.1, 3.3, 2.1 Hz, 1 H, 11-H), 3.80 (dd, *J* = 11.0, 4.1 Hz, 1 H, 6'-H), 3.83 (dd, *J* = 9.7, 9.1 Hz, 1 H, 9-H), 4.03 (dd, *J* = 9.2, 8.5 Hz, 1 H, 4-H), 4.15 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.27 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.39 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.43-4.49 (m, 5 H, C*H*$_2$-Ph), 4.60 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 4.70 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 4.73 (d, *J* = 11.1 Hz, 1 H, *CH*$_2$-Ph), 4.80 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 4.82 (d, *J* = 10.7 Hz, 1 H, *CH*$_2$-Ph), 5.40 (d, *J* = 3.5 Hz, 1 H, 7-H), 7.05–7.26 (m, 30 H, arom H).

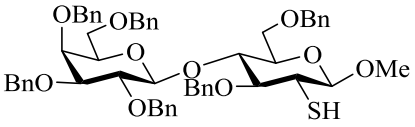
^{13}C NMR (75 MHz, $CDCl_3$): δ = 44.7 (d, C-2), 56.9 (q, O*Me*), 68.4, 69.1 (2t, C-6, C-12), 70.8 (t, C*H*$_2$-Ph), 71.1, 72.7 (2d, C-11, C-4), 73.0, 73.3, 73.4, 75.0 (4t, C*H*$_2$-Ph), 75.1 (d, C-5), 75.5 (t, C*H*$_2$-Ph), 77.6, 79.4, 81.8, 84.3 (4d, C-10, C-8, C-9, C-3), 96.6, 104.6 (2d, C-7, C-1), 127.4, 127.5, 127.6, 127.6, 127.7, 127.7, 127.8, 127.8, 128.0, 128.2, 128.3 (m, arom C-H), 137.8, 137.8, 137.9, 138.2, 138.3, 138.7 (6q, arom. *C*-CH_2O).

IR (film): ν = 3024, 2867, 1495, 1357, 1086, 1024, 729, 693 cm^{-1}.

Anal. calcd for $C_{55}H_{60}O_{10}S$ (913.12): C 72.34, H 6.62, S 3.51; found: C 72.14, H 6.63, S 3.57.

Methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2-thio-*β*-D-lactopyranoside (*β-lacto*-23):

Nature = White solid (425 mg, 93%).
R_f = 0.51 (hexane/ethyl acetate 8:2).
$[\alpha]_D^{20}$ = + 7.4 (c = 1.02 in $CHCl_3$).
m.p. = 107–108 °C.



β-lacto-**23**

^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.00 (d, *J* = 2.6 Hz, 1 H, S*H*), 2.96 (ddd, *J* = 10.5, 8.3, 2.6 Hz, 1 H, 2-H), 3.25 (dd, *J* = 10.9, 5.0 Hz, 1 H, 6-H), 3.29 (dd, *J* = 10.5, 8.6 Hz, 1 H, 3-H), 3.29–3.32 (m, 1 H, 5-H), 3.31 (dd, *J* = 9.8, 3.0 Hz, 1 H, 9-H), 3.33 (ddd, *J* = 3.7, 1.5, 1.0 Hz, 1 H, 11-H), 3.43 (dd, *J* = 10.9, 4.0 Hz, 1 H, 6'-H), 3.43 (s, 3 H, O*Me*), 3.63 (dd, *J* = 10.9, 1.5 Hz, 1 H, 12-H), 3.70 (dd, *J* = 9.8, 7.5 Hz, 1 H, 8-H), 3.77 (dd, *J* = 10.9, 3.7 Hz, 1 H, 12'-H), 3.83 (dd, *J* = 3.0, 1.0 Hz, 1 H, 10-H), 3.89 (dd, *J* = 10.2, 8.6 Hz, 1 H, 4-H), 4.12 (d, *J* = 8.3 Hz, 1 H, 1-H), 4.13 (d, *J* = 11.6 Hz, 1 H, CH_2-Ph), 4.24 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.30 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.32 (d, *J* = 7.5 Hz, 1 H, 7-H), 4.46 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.48 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.51 (d, *J* = 10.6 Hz, 1 H, CH_2-Ph), 4.61 (d, *J* = 12.1 Hz, 1 H, CH_2-Ph), 4.64 (d, *J* = 12.1 Hz, 1 H, CH_2-Ph), 4.72 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 4.74 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 4.89 (d, *J* = 11.6 Hz, 1 H, CH_2-Ph), 5.04 (d, *J* = 10.6 Hz, 1 H, CH_2-Ph), 7.05–7.30 (m, 30 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 45.8 (d, C-2), 56.9 (q, O*Me*), 68.0, 68.0 (2t, C-6, C-12), 72.6 (t, CH_2-Ph), 73.0 (d, C-9), 73.1, 73.4 (2t, CH_2-Ph), 73.7 (d, C-8), 74.7, 75.0, 75.3 (3t, CH_2-Ph), 75.5, 76.8, 79.9, 82.4, 82.9 (5d, C-11, C-4, C-10, C-5, C-3), 102.7, 104.6 (2d, C-7, C-1), 127.3, 127.4, 127.4, 127.5, 127.6, 127.6, 127.7, 127.8, 127.8, 128.0, 128.1, 128.2, 128.2, 128.3, 128.4 (m, arom C-H), 138.0, 138.2, 138.5, 138.5, 138.7, 139.0 (6q, arom. *C*-CH_2O).

IR (film): ν = 3029, 2862, 1495, 1364, 1098, 1024, 732, 695 cm^{-1}.

Anal. calcd for $C_{55}H_{60}O_{10}S$ (913.13): C 72.34, H 6.62, S 3.51; found: C 72.02, H 6.44, S 3.69.

General procedure for the Birch reduction of 2-thiocyanates (4a–9a) to 2-thiols (24–31).

Ammonia (50 mL) was condensed in a three necked round bottom flask at –78 °C using dry ice-acetone bath. Small pieces of freshly cut sodium (5 equiv per benzyl group) were added and the resulting blue colored solution was stirred for 5 min. At this temperature, a solution of the appropriate 2-thiocyanate **4a**–**9a** (0.5 mmol) in dry tetrahydrofuran (3 mL) was added followed by a few drops of methanol and it was then vigorously stirred for 10 min. The reaction mixture was quenched by a slow addition of solid ammonium chloride and ammonia was allowed to evaporate (approx. 1–2 h). The resulting crude residue was purified by silica gel column chromatography (dichloromethane/methanol 90:10) followed by lyophilization to afford the 2-thiols **24**–**21** in pure form.

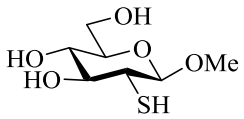
Note! The blue color of the reducing mixture persists until the completion of reaction; which turns to white upon quenching by ammonium chloride.

Methyl-2-deoxy-2-thio-*β*-D-glucopyranoside (*β-gluco*-24):

Nature = White solid (82 mg, 78%).

R_f= 0.33 (dichloromethane/methanol 8:2).

$[\alpha]_D^{20}$ = –8.9 (c = 0.96 in H_2O).



β-gluco-**24**

m.p. = 126–127 °C.

^{1}H NMR (500 MHz, D_2O): δ = 2.70 (dd, *J* = 10.2, 8.8 Hz, 1 H, 2-H), 3.34 (dd, *J* = 10.2, 8.9 Hz, 1 H, 3-H), 3.40 (dd, *J* = 9.6, 8.9 Hz, 1 H, 4-H), 3.47 (ddd, *J* = 9.6, 6.0, 2.2 Hz, 1 H, 5-H), 3.55 (s, 3 H, O*Me*), 3.72 (dd, *J* = 12.3, 6.0 Hz, 1 H, 6-H), 3.91 (dd, *J* = 12.3, 2.2 Hz, 1 H, 6'-H), 4.41 (d, *J* = 8.8 Hz, 1 H, 1-H).

^{13}C NMR (75 MHz, D_2O): δ = 47.1 (d, C-2), 58.1 (q, O*Me*), 61.7 (t, C-6), 71.5, 76.8, 77.4 (3d, C-4, C-5, C-3), 105.2 (d, C-1).

IR (film): *v* = 3356, 2927, 1591, 1447, 1379, 1064, 819, 603 cm^{-1}.

HRMS (EI): *m/z* $[M + H]^+$ Calcd for $C_7H_{14}O_5S$: 211.0665; found: 211.0654.

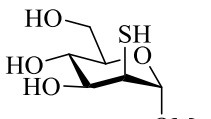
Anal. calcd for $C_7H_{14}O_5S$ (210.24): C 39.99, H 6.71, S 15.25; found: C 40.59, H 6.84, S 15.41.

Methyl-2-deoxy-2-thio-*α*-D-mannopyranoside (*α-manno*-25):

Nature = White solid (79 mg, 75%).

R_f = 0.34 (dichloro methane/methanol 8:2).

$[\alpha]_D^{20}$ = –143.9 (c = 0.99 in H_2O).



α-manno-**25**

m.p. = 108–109 °C.

^{1}H NMR (600 MHz, D_2O): δ = 3.37 (s, 3 H, O*Me*), 3.41 (d, *J* = 5.4 Hz, 1 H, 2-H), 3.60 (dd, *J* = 9.5, 5.4 Hz, 1 H, 3-H), 3.63–3.67 (m, 1H, 5-H), 3.74 (dd, *J* = 12.2, 5.4 Hz, 1 H, 6-H), 3.84 (dd, *J* = 12.2, 5.4 Hz, 1 H, 6'-H), 4.00 (dd, *J* = 9.5, 4.6 Hz, 1 H, 4-H), 4.90 (s, 1 H, 1-H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 44.4 (d, C-2), 54.8 (q, O*Me*), 60.6 (t, C-6), 66.4, 69.0, 72.9 (3d, C-4, C-5, C-3), 102.4 (d, C-1).

IR (Film): *v* = 3381, 2919, 1653, 1346, 1195, 1024, 952, 600 cm^{-1}.

HRMS (EI): *m/z* $[M + H]^+$ Calcd for $C_7H_{14}O_5S$: 211.0665; found: 211.0648.

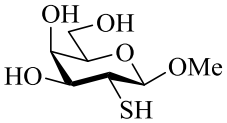
Anal. calcd for $C_7H_{14}O_5S$ (210.24): C 39.99, H 6.71, S 15.25; found: C 37.65, H 6.25, S 15.22.

Methyl-2-deoxy-2-thio-*β*-D-galactopyranoside (*β-galacto*-26):

Nature = white solid (68 mg, 65%).

R_f = 0.34 (dichloromethane/methanol 8:2).

$[\alpha]_D^{20}$ = +13.6 (c = 0.95 in H_2O).



β-galacto-**26**

m.p. = 136-137 °C.

Yield = ^{1}H NMR (500 MHz, D_2O): δ = 2.89 (dd, *J* = 11.4, 8.8 Hz, 1 H, 2-H), 3.56 (s, 3 H, O*Me*), 3.58 (dd, *J* = 11.4, 3.4 Hz, 1 H, 3-H), 3.69 (dd, *J* = 7.9, 4.1 Hz, 1 H, 5-H), 3.73 (dd, *J* = 11.4, 7.9 Hz, 1 H, 6-H), 3.78 (dd, *J* = 11.4, 4.1 Hz, 1 H, 6'-H), 3.86 (d, *J* = 3.4 Hz, 1 H, 4-H), 4.34 (d, *J* = 8.8 Hz, 1 H, 1-H).

^{13}C NMR (125 MHz, D_2O): δ = 42.8 (d, C-2), 57.0 (q, O*Me*), 60.9 (t, C-6), 67.7, 73.6, 75.0 (3d, C-4, C-3, C-5), 104.7 (d, C-1).

IR (Film): *v* = 3298, 2912, 2533, 1444, 1378, 1117, 1046, 866, 638 cm^{-1}.

Anal. calcd for $C_7H_{14}O_5S$ (210.24): C 39.99, H 6.71, S 15.25; found: C 38.94, H 6.57, S 15.20.

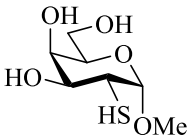
Methyl-2-deoxy-2-thio-α-D-galactopyranoside (*α-galacto*-27):

Nature = White solid (75 mg, 71%).

R_f = 0.34 (dichloro methane/methanol 8:2).

$[\alpha]_D^{20}$ = –142.1 (c = 1.03 in H_2O).

m.p. = 111–112 °C.



α-galacto-**27**

^{1}H NMR (500 MHz, D_2O): δ = 3.26 (dd, *J* = 5.3, 1.0 Hz, 1 H, 2-H), 3.38 (s, 3 H, O*Me*), 3.74 (dd, *J* = 11.7, 4.1 Hz, 1 H, 6-H), 3.81 (dd, *J* = 11.7, 7.9 Hz, 1 H, 6'-H), 3.89–3.92 (m, 1 H, 5-H), 3.90 (dd, *J* = 3.4, 1.4 Hz, 1 H, 4-H), 4.09 (dd, *J* = 5.3, 3.4 Hz, 1 H, 3-H), 5.02 (d, *J* = 1.0 Hz, 1 H, 1-H).

^{13}C NMR (125 MHz, D_2O): δ = 42.2 (d, C-2), 55.7 (q, O*Me*), 62.3 (t, C-6), 65.6, 69.5, 72.0 (3d, C-3, C-4, C-5), 104.7 (d, C-1).

IR (film): *v* = 3332, 2904, 2068, 1660, 1334, 1111, 1038, 952, 759 cm^{-1}.

HRMS (ESI-TOF): *m/z* $[M + Na]^+$ Calcd for $C_7H_{14}O_5NaS$: 233.0460; found: 233.0463.

Methyl-2-deoxy-2-thio-β-D-xylopyranoside (*β-xylo*-28):

Nature = White solid (62 mg, 69%).

R_f = 0.55 (hexane/ethyl acetate 1:9).

$[\alpha]_D^{20}$ = –18.2 (c = 1.05 in $CHCl_3$).

m.p. = 100–101 °C.

β-xylo-**28**

^{1}H NMR (300 MHz, D_2O): δ = 2.68 (dd, *J* = 10.4, 8.8 Hz, 1 H, 2-H), 3.33 (dd, *J* = 10.8, 6.0 Hz, 1 H, 5-H), 3.35 (dd, *J* = 10.4, 3.4 Hz, 1 H, 3-H), 3.53 (s, 3 H, O*Me*), 3.57 (ddd, *J* = 6.0, 5.5, 3.4 Hz, 1 H, 4-H), 4.00 (dd, *J* = 10.8, 5.5 Hz, 1 H, 5'-H), 4.35 (d, *J* = 8.8 Hz, 1 H, 1-H).

^{13}C NMR (75 MHz, D_2O): δ = 46.5 (d, C-2), 57.7 (q, O*Me*), 65.6 (t, C-5), 70.5, 76.9 (2d, C-4, C-3), 105.6 (d, C-1).

IR (film): *v* = 3390, 2922, 1667, 1452, 1148, 1057, 805 cm^{-1}.

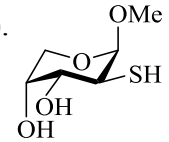
HRMS (ESI-TOF): *m/z* $[M + Na]^+$ Calcd for $C_6H_{12}O_4NaS$: 203.0354; found: 203.0347.

Methyl-2-deoxy-2-thio-*β*-D-arabinopyranoside (*β-arabino*-29):

Nature = Colorless viscous liquid (60 mg, 67%).

R_f = 0.55 (hexane/ethyl acetate 1:9).

$[\alpha]_D^{20}$ = –68.7 (c = 1.07 in $CHCl_3$).



β-arabino-**29**

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.96 (dd, *J* = 5.3, 3.9 Hz, 1 H, 2-H), 3.39 (s, 3 H, O*Me*), 3.65 (dd, *J* = 12.9, 8.5 Hz, 1 H, 5-H), 3.78 (dd, *J* = 12.9, 3.9 Hz, 1 H, 5'-H), 3.79 (dd, *J* = 8.5, 3.9 Hz, 1 H, 4-H), 3.99 (t, *J* = 3.9 Hz, 1 H, 3-H), 4.57 (d, *J* = 5.3 Hz, 1 H, 1-H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 44.0 (d, C-2), 56.4 (q, O*Me*), 63.3 (t, C-5), 68.0, 68.4 (2d, C-3, C-4), 102.9 (d, C-1).

IR (film): *v* = 3387, 2987, 2548, 1651, 1457, 1204, 1086, 791, 476 cm^{-1}.

HRMS (ESI-TOF): *m/z* $[M + Na]^+$ Calcd for $C_6H_{12}O_4NaS$: 203.0354; found: 203.0360.

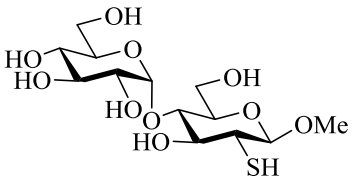
Methyl-2-deoxy-2-thio-*β*-D-maltopyranoside (*β-malto*-30):

Nature = White solid (127 mg, 68%).

R_f = 0.22 (dichloromethane/methanol 8:2).

$[\alpha]_D^{20}$ = + 44.3 (c = 0.98 in H_2O).

m.p. = 174–176 °C.



β-malto-**30**

^{1}H NMR (600 MHz, D_2O): δ = 2.76 (dd, *J* = 11.0, 8.6 Hz, 1 H, 2-H), 3.42 (dd, *J* = 11.0, 9.0 Hz, 1 H, 3-H), 3.58 (s, 3 H, O*Me*), 3.58 (dd, *J* = 9.8, 3.7 Hz, 1 H, 8-H), 3.62 (ddd, *J* = 8.9, 5.0, 2.1 Hz, 1 H, 11-H), 3.62–3.64 (m, 1 H, 10-H), 3.68 (dd, *J* = 10.2, 9.0 Hz, 1 H, 4-H), 3.70–3.74 (m, 1 H, 9-H), 3.72 (ddd, *J* = 10.2, 4.5, 2.1 Hz, 1 H, 5-H), 3.77 (dd, *J* = 12.6, 5.0 Hz, 1 H, 12-H), 3.79 (dd, *J* = 12.1, 4.5 Hz, 1 H, 6-H), 3.86 (dd, *J* = 12.6, 2.1 Hz, 1 H, 12'-H), 3.95 (dd, *J* = 12.1, 2.1 Hz, 1 H, 6'-H), 4.45 (d, *J* = 8.6 Hz, 1 H, 1-H), 5.41 (d, *J* = 3.7 Hz, 1 H, 7-H).

^{13}C APT NMR (150 MHz, D_2O): δ = 45.9 (d, C-2), 56.9 (q, O*Me*), 60.1, 60.3 (2t, C-6, C-12), 68.9, 71.3, 72.3, 72.4, 74.1, 76.4, 77.2 (7d, C-3, C-8, C-4, C-9, C-10, C-5, C-11), 99.3, 103.8 (2d, C-7, C-1).

IR (film): *v* = 3376, 2924, 1633, 1400, 1194, 1113, 1025, 800, 600 cm^{-1}.

HRMS (ESI-TOF): *m/z* $[M + Na]^+$ Calcd for $C_{13}H_{24}O_{10}NaS$: 395.0988; found: 395.1010

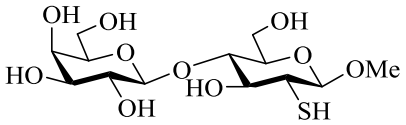
Methyl-2-deoxy-2-thio-*β*-D-lactopyranoside (*β-lacto*-31):

Nature = White solid (130 mg, 70%).

R_f = 0.23 (dichloromethane/methanol 8:2).

$[\alpha]_D^{20}$ = +4.1 (c = 1.05 in H_2O).

m.p. = 190–191 °C.



β-lacto-**31**

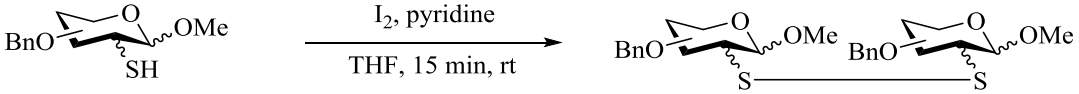
^{1}H NMR (600 MHz, D_2O): δ = 2.75 (dd, *J* = 10.5, 8.7 Hz, 1 H, 2-H), 3.54 (dd, *J* = 10.1, 7.5 Hz, 1 H, 8-H), 3.57 (s, 3 H, O*Me*), 3.60 (dd, *J* = 11.2, 1.2 Hz, 1 H, 12-H), 3.61-3.64 (m, 1 H, 11-H), 3.63 (dd, *J* = 9.1, 7.5 Hz, 1 H, 4-H), 3.67 (dd, *J* = 10.1, 3.3 Hz, 1 H, 9-H), 3.72-3.74 (m, 1 H, 5-H), 3.74 (dd, *J* = 10.5, 9.1 Hz, 1 H, 3-H), 3.77 (dd, *J* = 11.2, 3.0 Hz, 1 H, 12'-H), 3.82 (dd, *J* = 12.2, 4.4 Hz, 1 H, 6-H), 3.93 (dd, *J* = 3.3, 1.1 Hz, 1 H, 10-H), 3.99 (dd, *J* = 12.2, 1.6 Hz, 1 H, 6'-H), 4.46 (d, *J* = 8.7 Hz, 1 H, 1-H), 4.46 (d, *J* = 7.5 Hz, 1 H, 7-H).

^{13}C APT NMR (150 MHz, D_2O): δ = 45.5 (d, C-2), 57.3 (q, O*Me*), 60.0, 61.0 (2t, C-6, C-12), 68.5, 70.9, 72.5, 74.7, 75.0, 75.3, 79.2 (7d, C-10, C-8, C-9, C-5, C-4, C-3, C-11), 103.0, 104.1 (2d, C-7, C-1).

IR (film): *v* = 3326, 2930, 1635, 1403, 1115, 1015, 891, 605 cm^{-1}.

HRMS (ESI): *m/z* $[M + Ma]^+$ Calcd for $C_{13}H_{24}O_{10}NaS$: 395.0988; found: 395.097.

General procedure for synthesis of the disulfides 15, 32–37.



16, 18–23 **15, 32–37**

The appropriate thiol (**16**, **18**–**23**) (0.25 mmol) was dissolved in dry tetrahydrofuran (3 mL) at room temperature under nitrogen atmosphere. Pyridine (50 mg, 0.625 mmol, 2.5 equiv) and iodine (32 mg, 0.25 mmol, 1 equiv) were added and the resulting brown colored solution was stirred for 15 min until TLC showed complete conversion. Then the reaction mixture was diluted with dichloromethane (25 mL), washed with 5% sodium thiosulfate ($Na_2S_2O_3.5H_2O$, 25 mL) and brine (25 mL), dried over sodium sulfate and concentrated. The crude residue was purified by silica gel column chromatography (petroleum ether/MTBE 80:20), affording the disulfides (**15**, **32**–**37**) in analytically pure form.

Bis[methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-glucopyranoside] (*β-gluco*-15):

Nature = Colorless viscous liquid (110 mg, 92%).

R_f = 0.20 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +136.9 (c = 0.83 in $CHCl_3$).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.71 (dd, *J* = 10.8, 8.6 Hz, 1 H, 2-H), 2.99 (ddd, *J* = 10.1, 4.2, 2.3 Hz, 1 H, 5-H), 3.49 (dd, *J* = 10.8, 8.7 Hz, 1 H, 3-H), 3.50 (s, 3 H, O*Me*), 3.52 (dd, *J* = 10.9, 2.3 Hz, 1 H, 6-H), 3.54 (dd, *J* = 10.1, 8.7 Hz, 1 H, 4-H), 3.56 (dd, *J* = 10.9, 4.2 Hz, 1 H, 6'-H), 4.35 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.45 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.80 (bs, 2 H, C*H*$_2$-Ph), 7.08–7.31 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 56.3 (q, O*Me*), 58.0 (d, C-2), 68.6 (t, C-6), 73.4 (t, C*H*$_2$-Ph), 74.4 (d, C-5), 74.7, 75.9 (2t, C*H*$_2$-Ph), 79.5, 81.3 (2d, C-3, C-4), 102.8 (d, C-1), 127.5, 127.6, 127.6, 127.7, 127.8, 128.2, 128.3, 128.4 (m, arom C-H), 138.1, 138.1, 138.1 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3029, 2862, 1952, 1604, 1453, 1357, 1106, 1044, 735, 695 cm^{-1}.

Anal. calcd for $C_{56}H_{62}O_{10}S_2$ (959.22): C 70.12, H 6.51, S 6.69; found: C 69.79, H 6.66, S 6.93.

Bis[methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-galactopyranoside] (*β-galacto*-32):

Nature = Colorless viscous oil (108 mg, 90%).

R_f = 0.17 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = +120.7 (c = 0.99 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.99 (dd, *J* = 11.4, 8.6 Hz, 1 H, 2-H), 3.17 (t, *J* = 6.5 Hz, 1 H, 5-H), 3.35 (s, 3 H, O*Me*), 3.43 (dd, *J* = 11.3, 6.5 Hz, 1 H, 6-H), 3.44–3.48 (m, 1 H, 6'-H), 3.49 (dd, *J* = 11.4, 4.0 Hz, 1 H, 3-H), 3.76 (dd, *J* = 6.5, 4.0 Hz, 1 H, 4-H), 4.29 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.32 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.38 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.0 Hz, 1 H, *CH*$_2$-Ph), 4.59 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 7.11–7.30 (m, 15 H, arom H).

^{13}C APT NMR (125 MHz, $CDCl_3$): δ = 55.1 (q, O*Me*), 56.5 (d, C-2), 68.6 (t, C-6), 72.3 (d, C-4), 72.8 (t, C*H*$_2$-Ph), 72.8 (d, C-5), 73.4 (t, C*H*$_2$-Ph), 74.6 (t, C*H*$_2$-Ph), 78.9 (d, C-3), 103.2 (d, C-1), 127.5, 127.7, 127.8, 127.8, 127.9, 128.0, 128.1 (m, arom. *C*-H), 137.7, 137.9, 138.3 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3480, 2863, 1723, 1496, 1453, 1355, 1098, 1061, 733, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{56}H_{63}O_{10}S_2$: 959.3863; found: 959.3792.

Anal. calcd for $C_{56}H_{62}O_{10}S_2$ (959.22): C 70.12, H 6.52, S 6.68; found: C 69.20, H 6.66, S 6.89.

Bis[methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2,2′-disulfido-α-D-galactopyranoside] (α-*galacto*-33):

Nature = Colorless viscous oil (111 mg, 93%).

R_f = 0.30 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = –14.4 (c = 1.03 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.19 (s, 3 H, O*Me*), 3.41 (d, *J* = 5.3 Hz, 1 H, 2-H), 3.50 (dd, *J* = 13.2, 6.3 Hz, 1 H, 6-H), 3.52 (dd, *J* = 13.2, 6.3 Hz, 1 H, 6'-H), 3.71 (s, 1 H, 4-H), 3.80 (t, *J* = 6.3 Hz, 1 H, 5-H), 3.95 (dd, *J* = 5.3, 2.2 Hz, 1 H, 3-H), 4.28 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.37 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.37 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.45 (d, *J* = 11.7 Hz, 1 H, *CH*$_2$-Ph), 4.60 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.92 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 5.06 (s, 1 H, 1-H), 7.09–7.29 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 54.9 (q, O*Me*), 56.9 (d, C-2), 69.3 (t, C-6), 70.0 (t, C*H*$_2$-Ph), 70.0 (d, C-5), 73.0 (d, C-4), 73.4 (t, C*H*$_2$-Ph), 74.1 (t, C*H*$_2$-Ph), 75.9 (d, C-3), 102.6 (d, C-1), 127.3, 127.5, 127.5, 127.6, 128.0, 128.1, 128.2, 128.3, (m, arom. *C*-H), 138.0, 138.0, 138.5 (3q, arom. *C*-CH_2O).

IR (film): v = 3028, 2908, 1722, 1605, 1496, 1453, 1352, 1094, 1052, 732, 695 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{56}H_{63}O_{10}S_2$: 959.3863; found: 959.3892.

Bis[methyl 3,4-di-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-xylopyranoside] (*β-xylo*-34):

Nature = Colorless viscous oil (78 mg, 87%).

R_f = 0.21 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +147.4 (c = 1.23 in $CHCl_3$).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.63 (dd, *J* = 9.6, 7.8 Hz, 1 H, 2-H), 2.89 (dd, *J* = 11.2, 9.7 Hz, 1 H, 5-H), 3.42 (s, 3 H, O*Me*), 3.34–3.52 (m, 2 H, 3-H, 4-H), 3.79 (dd, *J* = 11.2, 4.2 Hz, 1 H, 5'-H), 4.32 (d, *J* = 7.8 Hz, 1 H, 1-H), 4.50 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.60 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.81 (d, *J* = 10.8 Hz, 1 H, *CH*$_2$-Ph), 7.15–7.32 (m, 10 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 56.3 (q, O*Me*), 57.3 (d, C-2), 62.8 (t, C-5), 72.8 (t, C*H*$_2$-Ph), 75.4 (t, C*H*$_2$-Ph), 78.9 (d, C-3), 79.5 (d, C-4), 103.3 (d, C-1), 127.6, 127.7, 127.8, 128.0, 128.4 (m, arom. *C*-H), 138.0, 138.2 (2q, arom. *C*-CH_2O).

IR (film): v = 3063, 3030, 2861, 1954, 1496, 1454, 1145, 1072, 737, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{40}H_{46}NaO_8S_2$: 741.2532; found: 741.2504.

Bis[methyl 3,4-di-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-arabinopyranoside] (*β-arabino*-35):

Nature = Colorless viscous oil (18 mg, 90%).

R_f = 0.22 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = –122.6 (c = 0.99 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.13 (dd, *J* = 4.8, 3.4 Hz, 1 H, 2-H), 3.30 (s, 3 H, O*Me*), 3.54 (dt, *J* = 6.4, 3.4 Hz, 1 H, 4-H), 3.68 (dd, *J* = 11.4, 3.4 Hz, 1 H, 5-H), 3.72 (dd, *J* = 11.4, 6.4 Hz, 1 H, 5'-H), 3.54 (t, *J* = 3.4 Hz, 1 H, 3-H), 4.58 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.67 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.67 (d, *J* = 12.3 Hz, 1 H, *CH*$_2$-Ph), 4.74 (d, *J* = 4.8 Hz, 1 H, 1-H), 7.17–7.33 (m, 10 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 55.9 (q, O*Me*), 59.5 (d, C-2), 62.1 (t, C-5), 71.9 (2t, CH_2-Ph), 74.7 (d, C-4), 75.4 (d, C-3), 102.0 (d, C-1), 127.5, 127.6, 127.6, 127.7, 128.2, 128.3 (m, arom. *C*-H), 138.2, 138.5 (2q, arom. *C*-CH_2O).

IR (film): *v* = 3444, 2924, 2871, 1723, 1496, 1453, 1120, 1053, 735, 697 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{40}H_{46}NaO_8S_2$: 741.2532; found: 741.2477.

Bis[methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-maltopyranoside] (*β*-*malto*-36):

Nature = Colorless viscous oil (196 mg, 86%).

R_f = 0.10 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +113.8 (c = 1.04 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.76–2.79 (m, 1 H, 11-H), 2.78 (dd, *J* = 10.8, 8.2 Hz, 1 H, 2-H), 3.36 (dd, *J* = 10.6, 1.8 Hz, 1 H, 6-H), 3.40 (dd, *J* = 9.8, 3.5 Hz, 1 H, 8-H), 3.44 (s, 3 H, O*Me*), 3.46 (dd, *J* = 11.3, 1.9 Hz, 1 H, 12-H), 3.50 (dd, *J* = 10.6, 2.8 Hz, 1 H, 6'-H), 3.52 (dd, *J* = 10.8, 8.8 Hz, 1 H, 3-H), 3.57 (dd, *J* = 10.1, 8.8 Hz, 1 H, 4-H), 3.65 (dd, *J* = 11.3, 3.6 Hz, 1 H, 12'-H), 3.69 (ddd, *J* = 10.1, 2.8, 1.8 Hz, 1 H, 5-H), 3.83 (dd, *J* = 9.8, 8.7 Hz, 1 H, 9-H), 3.93 (dd, *J* = 9.6, 8.7 Hz, 1 H, 10-H), 4.26 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.29 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.39 (d, *J* = 12.3 Hz, 1 H, CH_2-Ph), 4.42 (s, 3 H, CH_2-Ph), 4.46 (d, *J* = 12.3 Hz, 1 H, CH_2-Ph), 4.52 (d, *J* = 12.0 Hz, 1 H, CH_2-Ph), 4.66 (d, *J* = 10.8 Hz, 1 H, CH_2-Ph), 4.71 (d, *J* = 10.8 Hz, 1 H, CH_2-Ph), 4.72 (d, *J* = 10.7 Hz, 1 H, CH_2-Ph), 4.78 (d, *J* = 10.7 Hz, 1 H, CH_2-Ph), 4.91 (d, *J* = 11.1 Hz, 1 H, CH_2-Ph), 5.40 (d, *J* = 3.5 Hz, 1 H, 7-H), 7.04–7.19 (m, 30 H, arom H).

^{13}C APT NMR (125 MHz, $CDCl_3$): δ = 56.1 (q, O*Me*), 57.4 (d, C-2), 68.2 (t, C-6), 68.7 (t, C-12), 71.5 (d, C-5), 73.2, 73.3, 73.4, 73.9 (4t, CH_2-Ph), 74.2, 74.9 (2d, C-11, C-10), 74.9, 75.4 (2t, CH_2-Ph), 77.7, 79.4, 81.4, 82.0 (4d, C-4, C-8, C-3, C-9), 97.1, 102.4 (2d, C-7, C-1), 127.1, 127.2, 127.3, 127.4, 127.5, 127.5, 127.6, 127.6, 127.7, 127.8, 127.9, 128.1, 128.2, 128.2, 128.3 (m, arom. *C*-H), 137.8, 137.9, 138.1, 138.3, 138.3, 138.6 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3502, 3029, 2864, 1702, 1605, 1496, 1207, 1027, 733, 695 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{110}H_{118}NaO_{20}S_2$: 1845.7556; found: 1845.7594.

Bis[methyl 3,6,8,9,10,12-hexa-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-lactopyranoside] (*β-lacto*-37):

Nature = Colorless viscous oil (203 mg, 89%).

R_f = 0.10 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +78.8 (c = 0.90 in $CHCl_3$).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.64 (dd, *J* = 10.9, 8.6 Hz, 1 H, 2-H), 2.95 (ddd, *J* = 9.6, 3.8, 1.4 Hz, 1 H, 5-H), 3.17 (dd, *J* = 9.8, 4.8 Hz, 1 H, 12-H), 3.23 (dd, *J* = 8.7, 5.7 Hz, 1 H, 10-H), 3.29 (dd, *J* = 9.8, 2.6 Hz, 1 H, 12'-H), 3.33 (dd, *J* = 9.6, 8.7 Hz, 1 H, 4-H), 3.39 (dd, *J* = 10.9, 8.7 Hz, 1 H, 3-H), 3.43 (s, 3 H, O*Me*), 3.48 (dd, *J* = 10.9, 1.4 Hz, 1 H, 6-H), 3.65 (dd, *J* = 9.8, 7.6 Hz, 1 H, 8-H), 3.67 (dd, *J* = 10.9, 3.8 Hz, 1 H, 6'-H), 3.79–3.81 (m, 1 H, 11-H), 3.87 (dd, *J* = 9.8, 8.7 Hz, 1 H, 9-H), 4.09 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.20 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.31 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.34 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.34 (d, *J* = 7.6 Hz, 1 H, 7-H), 4.42 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.57 (d, *J* = 11.9 Hz, 1 H, C*H*$_2$-Ph), 4.60 (d, *J* = 11.9 Hz, 1 H, C*H*$_2$-Ph), 4.71 (s, 2 H, C*H*$_2$-Ph), 4.85 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 5.05 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 6.94–7.29 (m, 30 H, arom H).

^{13}C APT NMR (150 MHz, $CDCl_3$): δ = 56.2 (q, O*Me*), 57.5 (d, C-2), 67.9, 67.9 (2t, C-6, C-12), 72.5 (t, C*H*$_2$-Ph), 72.8 (d, C-10), 73.0, 73.3 (2t, C*H*$_2$-Ph), 73.5 (d, C-11), 74.6 (t, C*H*$_2$-Ph), 74.6 (d, C-5), 70.0, 75.3 (2t, C*H*$_2$-Ph), 77.6, 79.3, 79.8, 82.3 (4d, C-9, C-3, C-8, C-4), 102.6, 102.7 (2d, C-7, C-1), 127.0, 127.2, 127.3, 127.4, 127.6, 127.6, 127.8, 127.8, 128.0, 128.1, 128.2, 128.3, 128.3 (m, arom. *C*-H), 137.9, 138.3, 138.4, 138.8, 138.8, 198.9 (6q, arom. *C*-CH_2O).

IR (film): *v* = 2868, 1605, 1496, 1453, 1361, 1065, 1026, 732, 695 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{110}H_{118}NaO_{20}S_2$: 1845.7556; found: 1845.7623.

Anal. calcd for $C_{110}H_{118}O_{20}S_2$ (1824.25): C 72.42, H 6.52, S 3.51; found: C 71.65, H 6.80, S 3.59.

Procedure for the synthesis of disulfide by control experiment (*β-gluco*-15).

To a stirred solution of thiol **16** (120 mg, 0.25 mmol) in dry dimethylformamide (2 mL) was added sodium hydride (60% dispersion in mineral oil, 20 mg, 0.5 mmol, 2 equiv) under argon at room temperasture. After stirring for 10 min, a solution of thiocyanate **4a** (126 mg, 0.25 mmol, 1

equiv) in dry dimethylformamide (2 mL) was added dropwise and the resulting solution was stirred for 1 h. Upon completion, the reaction mixture was quenched by ice-water (25 mL) and extracted with diethyl ether (3 x 25 mL). The combined organic layer were washed with brine, dried over sodium sulfate, concentrated and purified by column chromatography to afford the disulfide **15** (183 mg, 76%) in analytically pure form.

Bis[methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2,2′-disulfido-*β*-D-glucopyranoside] (*β-gluco*-15):

Nature = Colorless viscous liquid (183 mg, 76%).

R_f = 0.20 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{20}$ = +136.9 (c = 0.83 in $CHCl_3$).

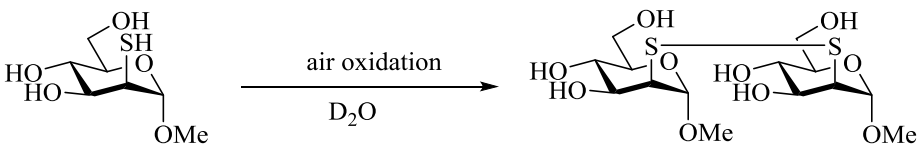
^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.71 (dd, *J* = 10.8, 8.6 Hz, 1 H, 2-H), 2.99 (ddd, *J* = 10.1, 4.2, 2.3 Hz, 1 H, 5-H), 3.49 (dd, *J* = 10.8, 8.7 Hz, 1 H, 3-H), 3.50 (s, 3 H, O*Me*), 3.52 (dd, *J* = 10.9, 2.3 Hz, 1 H, 6-H), 3.54 (dd, *J* = 10.1, 8.7 Hz, 1 H, 4-H), 3.56 (dd, *J* = 10.9, 4.2 Hz, 1 H, 6'-H), 4.35 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.45 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.80 (bs, 2 H, C*H*$_2$-Ph), 7.08–7.31 (m, 15 H, arom H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 56.3 (q, O*Me*), 58.0 (d, C-2), 68.6 (t, C-6), 73.4 (t, C*H*$_2$-Ph), 74.4 (d, C-5), 74.7, 75.9 (2t, C*H*$_2$-Ph), 79.5, 81.3 (2d, C-3, C-4), 102.8 (d, C-1), 127.5, 127.6, 127.6, 127.7, 127.8, 128.2, 128.3, 128.4 (m, arom C-H), 138.1, 138.1, 138.1 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3029, 2862, 1952, 1604, 1453, 1357, 1106, 1044, 735, 695 cm^{-1}.

Anal. calcd for $C_{56}H_{62}O_{10}S_2$ (959.22): C 70.12, H 6.51, S 6.69; found: C 69.79, H 6.66, S 6.93.

Procedure for the synthesis of the disulfide 38.



α-manno-**25** *α-manno*-**38** (complete conversion)

A solution of thiol **25** (70 mg, 0.3 mmol) in water (1 mL) was allowed to stir under air for 24 h until TLC showed complete converstion. The solvent was removed by lyophilization to afford the disulfide **38** (70 mg, 99%) in pure form.

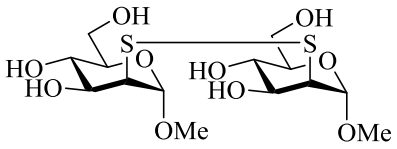
Bis[methyl-2-deoxy-2,2′-disulfido-α-D-mannopyranoside] (*α-manno*-38):

Nature = White solid (70 mg, 99%).

R_f = 0.23 (dichloro methane/methanol 8:2).

$[\alpha]_D^{20}$ = –149.2 (c = 0.95 in H_2O).

m.p. = 110–111 °C.



α-manno-**38**

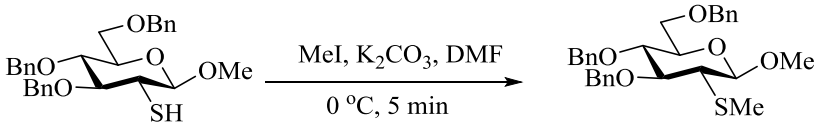
^{1}H NMR (300 MHz, D_2O): δ = 3.41 (s, 3 H, O*Me*), 3.47-3.52 (m, 2 H, 2-H, 3-H), 3.62 (ddd, *J* = 9.6, 5.8, 1.8 Hz,1 H, 5-H), 3.73 (dd, *J* = 12.4, 5.8 Hz, 1 H, 6-H), 3.84 (dd, *J* = 12.4, 1.8 Hz, 1 H, 6'-H), 4.11 (dd, *J* = 9.6, 5.1 Hz, 1 H, 4-H), 5.10 (s, 1 H, 1-H).

^{13}C NMR (75 MHz, D_2O): δ = 54.6 (q, O*Me*), 59.3 (d, C-2), 60.4 (t, C-6), 67.1, 69.0, 72.5 (3d, C-3, C-4, C-5), 100.4 (d, C-1).

IR (Film): *v* = 3344, 1645, 1408, 1237, 1072, 618 cm^{-1}.

Anal. calcd for $C_{14}H_{26}O_{10}S_2$ (418): C 40.18, H 6.26, S 15.32; found: C 38.30, H 6.29, S 15.39.

Procedure for the synthesis of the *S*-methyl derivative of thiol 16.



β-gluco-**16** *β-gluco*-**39**

To a solution of thiol **16** (144 mg, 0.3 mmol) in dry dimethylformamide (2 mL) was added potassium carbonate (41 mg, 0.3 mmol, 1 equiv) at 0 °C under nitrogen atmosphere and it was stirred for 10 min. At this temperature, methyl iodide (43 mg, 0.3 mmol, 1 equiv) was added and continued the stirring for 5 min. Upon completion, the reaction mixture was diluted with diethyl ether (15 mL) and extracted with water (25 mL). The aqueous layer was further extracted with diethyl ether (3 X 25 mL) and the combined organic layers were washed with brine (25 mL),

dried over sodium sulfate, concentrated and purified by silica gel column chromatography (hexane/MTBE 85:15) to afford the thiomethyl sugar **39** in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thiomethyl-*β*-D-glucopyranoside (*β-gluco*-39):

Nature = Colorless viscous oil (104 mg, 70%).

R_f = 0.47 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = +23.9 (c = 0.30 in $CHCl_3$).

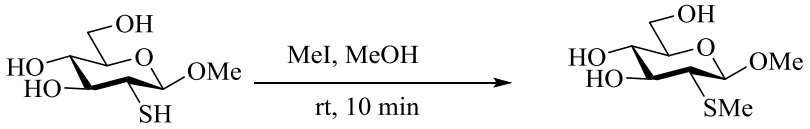
^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.20 (s, 3 H, S*Me*), 2.60 (dd, *J* = 10.9, 8.7 Hz, 1 H, 2-H), 3.33 (dd, *J* = 10.9, 8.7 Hz, 1 H, 3-H), 3.38 (ddd, *J* = 9.6, 4.4, 2.3 Hz, 1 H, 5-H), 3.49 (s, 3 H, O*Me*), 3.54 (dd, *J* = 9.6, 8.7 Hz, 1 H, 4-H), 3.63 (dd, *J* = 10.8, 4.4 Hz, 1 H, 6-H), 3.68 (dd, *J* = 10.8, 2.3 Hz, 1 H, 6'-H), 4.18 (d, *J* = 8.7 Hz, 1 H, 1-H), 4.48 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.89 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 7.08–7.34 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 16.3 (q, S*Me*), 54.4 (d, C-2), 57.1 (q, O*Me*), 68.9 (t, C-6), 73.5 (t, C*H*$_2$-Ph), 74.9 (d, C-5), 74.9, 76.1 (2t, C*H*$_2$-Ph), 79.1, 83.1 (2d, C-4, C-3), 105.6 (d, C-1), 127.6, 127.7, 127.8, 128.0, 128.3, 128.3, 128.4 (m, arom. *C*-H), 138.0, 138.1, 138.3 (3q, arom. *C*-CH_2O).

IR (film): *v* = 2862, 1496, 1453, 1357, 1109, 1047, 736, 696 cm^{-1}.

Anal. calcd for $C_{29}H_{34}O_5S$ (494.64): C 70.42, H 6.93, S 6.48; found: C 10.31, H 6.47, S 6.77.

Procedure for the synthesis of the *S*-methyl derivative 40.



β-gluco-**24** *β-gluco*-**40**

The thiol **24** (100 mg, 0.48 mmol) was dissolved in dry methanol (2 mL) at room temperature under argon atmosphere. Triethyl amine (146 mg, 1.44 mmol, 3 equiv) and methyl iodide (204 mg, 1.44 mmol, 3 equiv) were added and the resulting solution was stirred for 10 min until TLC

showed complete conversion. Then the solvent was removed *in vacuo* and the crude residue was purified by filtration through a pad of silica gel (dichloromethane/methanol 90:10) to afford the thiomethyl sugar **40** in analytically pure form.

Methyl-2-deoxy-2-thiomethyl-*β*-D-glucopyranoside (*β-gluco*-40):

Nature = White solid (101 mg, 94%).

R_f = 0.40 (dichloromethane/methanol 8:2).

$[\alpha]_D^{24}$ = –14.8 (c = 1.01 in H_2O).

m.p. = 96–97 °C.

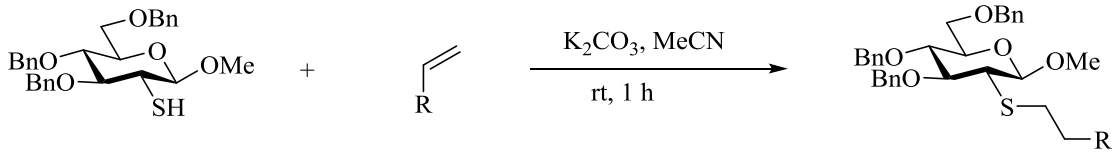
^{1}H NMR (300 MHz, D_2O): δ = 2.18 (s, 3 H, S*Me*), 2.45 (dd, *J* = 10.4, 8.9 Hz, 1 H, 2-H), 3.35–3.41 (m, 1 H, 5-H), 3.42 (dd, *J* = 9.3, 8.3 Hz, 1 H, 4-H), 3.49 (dd, *J* = 10.4, 8.3 Hz, 1 H, 3-H), 3.59 (s, 3 H, O*Me*), 3.73 (dd, *J* = 12.3, 5.6 Hz, 1 H, 6-H), 3.93 (dd, *J* = 12.3, 1.9 Hz, 1 H, 6'-H), 4.52 (d, *J* = 8.9 Hz, 1 H, 1-H).

^{13}C APT NMR (75 MHz, D_2O): δ = 13.1 (q, S*Me*), 53.1 (d, C-2), 57.5 (q, O*Me*), 61.2 (t, C-6), 71.2, 73.1, 76.0 (3d, C-5, C-4, C-3), 103.6 (d, C-1).

IR (film): *v* = 3453, 3414, 3353, 2919, 2835, 1450, 1371, 1124, 1045, 1024, 805, 617 cm^{-1}.

Anal. calcd for $C_8H_{16}O_5S$ (224.27): C 42.84, H 7.19, S 14.30; found: C 42.81, H 7.17, S 14.41.

General procedure for the Sulfa-Michael addition (SMA) of thiol 16.



β-gluco-**16** **41** R = CN, COMe, COOEt (**42–44**)

To a stirred solution of thiol **16** (120 mg, 0.25 mmol) in dry acetonitrile (2 mL) was added the corresponding Michael acceptor **41** (0.50 mmol, 2 equiv) under argon atmosphere. Potassium carbonate (69 mg, 0.50 mmol, 2 equiv) was added and the resulting reaction mixture was stirred for 1 h at room temperature until TLC showed complete conversion. The solvent was removed *in vacuo* and the crude residue was purified by silica gel chromatography (petroleum ether/MTBE 70:30) to afford the products **42**–**44** in analytically pure form.

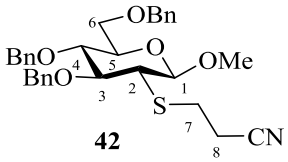
Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(propanenitrile)-*β*-D-glucopyranoside (*β-gluco*-42):

Nature = White solid (111 mg, 83%).

R_f = 0.24 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = –19.4 (c = 1.06 in $CHCl_3$).

m.p. = 52–53 °C.



42

^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.49 (ddd, *J* = 16.9, 7.5, 6.8 Hz, 1 H, 7-H), 2.57 (dd, *J* = 10.9, 8.6 Hz, 1 H, 2-H), 2.57 (ddd, *J* = 16.9, 7.5, 6.8 Hz, 1 H, 7'-H), 2.77 (ddd, *J* = 13.9, 7.5, 6.8 Hz, 1 H, 8-H), 2.96 (ddd, *J* = 13.9, 7.5, 6.8 Hz, 1 H, 8'-H), 3.26 (dd, *J* = 10.9, 9.0 Hz, 1 H, 3-H), 3.35 (ddd, *J* = 9.7, 4.1, 2.2 Hz, 1 H, 5-H), 3.47 (s, 3 H, O*Me*), 3.55 (dd, *J* = 9.7, 9.0 Hz, 1 H, 4-H), 3.62 (dd, *J* = 10.9, 4.1 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.9, 2.2 Hz, 1 H, 6'-H), 4.14 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.45 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.47 (d, *J* = 11.1 Hz, 1 H, CH_2-Ph), 4.53 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.72 (d, *J* = 10.9 Hz, 2 H, CH_2-Ph), 4.80 (d, *J* = 11.1 Hz, 1 H, CH_2-Ph), 7.07–7.31 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 18.8 (t, C-8), 28.9 (t, C-7, SCH_2), 53.4 (d, C-2), 57.2 (q, O*Me*), 68.5 (t, C-6), 73.4 (t, CH_2-Ph), 74.6 (d, C-5), 74.8, 76.3 (2t, CH_2-Ph), 79.0, 82.6 (2d, C-4, C-3), 105.4 (d, C-1), 118.4 (q, CN), 127.5, 127.6, 127.7, 127.7, 127.9, 128.2, 128.3 (m, arom. *C*-H), 137.8, 137.9, 137.9 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3062, 2865, 2246, 1726, 1496, 1453, 1358, 1109, 1072, 1049, 742, 700 cm^{-1}.

Anal. calcd for $C_{31}H_{35}NO_5S$ (533.68): C 69.77, H 6.61, N 2.62, S 6.01; found: C 69.29, H 6.59, N 2.59, S 5.91.

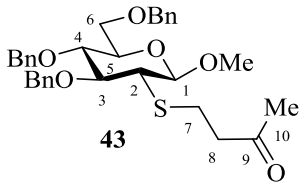
Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(butan-2-one)-*β*-D-glucopyranoside (*β-gluco*-43):

Nature = White solid (100 mg, 73%).

R_f = 0.33 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = –12.7 (c = 1.03 in $CHCl_3$).

m.p. = 48–49 °C.



43

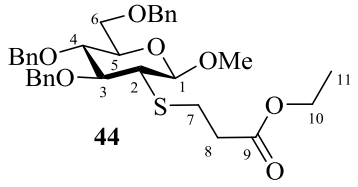
^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.97 (s, 3 H, *Me*), 2.60 (dd, *J* = 10.9, 8.6 Hz, 1 H, 2-H), 2.61 (ddd, *J* = 17.7, 7.6, 6.4 Hz, 1 H, 7-H, S*CH*$_2$), 2.68 (ddd, *J* = 17.7, 7.6, 6.4 Hz, 1 H, 7'-H, S*CH*$_2$), 2.79 (ddd, *J* = 13.9, 7.6, 6.4 Hz, 1 H, 8-H), 2.90 (ddd, *J* = 13.9, 7.6, 6.4 Hz, 1 H, 8'-H), 3.26 (dd, *J* = 10.9, 8.6 Hz, 1 H, 3-H), 3.35 (ddd, *J* = 9.9, 4.5, 2.2 Hz, 1 H, 5-H), 3.47 (s, 3 H, O*Me*), 3.54 (dd, *J* = 9.9, 8.6 Hz, 1 H, 4-H), 3.62 (dd, *J* = 10.9, 4.5 Hz, 1 H, 6-H), 3.66 (dd, *J* = 10.9, 2.2 Hz, 1 H, 6'-H), 4.14 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.46 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.82 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 7.08–7.30 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 26.6 (d, C-7, S*CH*$_2$), 29.9 (q, *Me*), 43.7 (d, C-8), 52.8 (d, C-2), 57.1 (q, O*Me*), 68.7 (t, C-6), 73.3 (t, C*H*$_2$-Ph), 74.6 (d, C-5), 74.8, 76.2 (2t, C*H*$_2$-Ph), 79.0, 83.0 (2d, C-4, C-3), 105.6 (d, C-1), 127.5, 127.6, 127.7, 127.8, 128.2, 128.3 (m, arom. *C*-H), 137.9, 138.0, 138.1 (3q, arom. *C*-CH_2O), 206.7 (*C*OMe).

IR (film): *v* = 3060, 3030, 2863, 1955, 1714, 1496, 1453, 1358, 1108, 1046, 737, 697 cm^{-1}.

Anal. calcd for $C_{32}H_{38}O_6S$ (550.71): C 69.79, H 6.96, S 5.82; found: C 69.68, H 6.98, S 5.54.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(propanoic acid ethyl ester)-*β*-D-glucopyranoside (*β-gluco*-44):



44

Nature = Colorless viscous liquid (121 mg, 83%).

R_f = 0.24 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = –19.6 (c = 1.09 in $CHCl_3$).

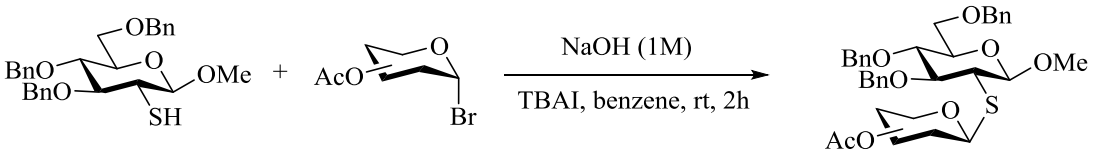
^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.97 (t, *J* = 7.0 Hz, 3 H, *Me*), 2.52 (dt, *J* = 16.5, 6.5 Hz, 1 H, 7-H, S*CH*$_2$), 2.56 (dt, *J* = 16.5, 6.5 Hz, 1 H, 7'-H, S*CH*$_2$), 2.65 (dd, *J* = 10.8, 8.7 Hz, 1 H, 2-H), 2.84 (ddd, *J* = 13.2, 8.0, 6.5 Hz, 1 H, 8-H), 2.97 (ddd, *J* = 13.2, 8.0, 6.5 Hz, 1 H, 8'-H), 3.26 (dd, *J* = 10.8, 8.8 Hz, 1 H, 3-H), 3.35 (ddd, *J* = 9.8, 4.5, 2.2 Hz, 1 H, 5-H), 3.46 (s, 3 H, O*Me*), 3.53 (dd, *J* = 9.8, 8.8 Hz, 1 H, 4-H), 3.61 (dd, *J* = 10.9, 4.5 Hz, 1 H, 6-H), 3.64 (dd, *J* = 10.9, 2.2 Hz, 1 H, 6'-H), 3.98 (dq, *J* = 10.8, 7.0 Hz, 1 H, 10-H, O*CH*$_2$), 4.03 (dq, *J* = 10.8, 7.0 Hz, 1 H, 10'-H O*CH*$_2$), 4.14 (d, *J* = 8.7 Hz, 1 H, 1-H), 4.44 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.45 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.84 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 7.06–7.30 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 14.0 (q, *Me*), 27.9 (t, C-7, S*CH*$_2$), 35.0 (t, C-8), 53.0 (d, C-2), 57.1 (q, O*Me*), 60.3 (t, C-10, O*CH*$_2$), 68.7 (t, C-6), 73.3 (t, C*H*$_2$-Ph), 74.6 (d, C-5), 74.8, 76.1(2t, C*H*$_2$-Ph), 79.0, 82.9 (2d, C-4, C-3), 105.7 (d, C-1), 127.4, 127.5, 127.6, 127.7, 127.8, 128.2, 128.2 (m, arom. *C*-H), 137.9, 138.0, 138.1 (3q, arom. *C*-CH_2O), 171.8 (*CO*OEt).

IR (film): *v* = 3060, 3027, 2920, 2863, 1732, 1496, 1369, 1107, 1046, 737, 697 cm^{-1}.

Anal. calcd for $C_{33}H_{40}O_7S$ (580.73): C 69.25, H 6.94, S 5.52; found: C 68.15, H 7.15, S 5.42.

General procedure for the synthesis of the (2→1) linked thiodisaccharides 46–49.



β-gluco-**16** **45c–f** **46–49**

To a solution of thiol **16** (120 mg, 0.25 mmol) in dry benzene (1 mL) was added a solution of sodium hydroxide (1M, 1 mL) followed by tetrabutylammonium iodide (92 mg, 0.25 mmol, 1 equiv). The resulting solution was allowed to stir for 5 min under nitrogen at room temperature. Then a solution of appropriate bromosugar **45c–f** (0.37 mmol, 1.5 equiv) in dry benzene (2 mL) was added and it was stirred for 2 h until TLC showed complete conversion. The reaction mixture was diluted with dichloromethane (25 mL) and extracted with water (25 mL). The aqueous layer was further extracted with dichloromethane (3 X 25 mL). The combined organic layers were washed with brine (25 mL), dried over sodium sulfate, concentrated and purified by silica gel column chromatography (petroleum ether/MTBE 60:40), affording thiodisaccharides **46–49** in analytically pure form.

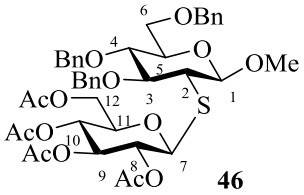
Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(8,9,10,12-tetra-*O*-acetyl-7-deoxy-*β*-D-glucopyrano)-*β*-D-glucopyranoside (*β-gluco*-46):

Nature = White solid (172 mg, 85%).

R_f = 0.29 (hexane/ethyl acetate 1:1).

$[\alpha]_D^{23}$ = –12.3 (c = 1.27 in $CHCl_3$).

m.p. = 104–105 °C.



46

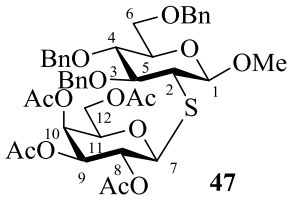
^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.78, 1.92, 1.94, 1.97 (4s, 12 H, OAc), 2.97 (dd, *J* = 10.9, 8.7 Hz, 1 H, 2-H), 3.38 (dt, *J* = 9.4, 3.0 Hz, 1 H, 11-H), 3.41 (dd, *J* = 10.9, 8.7 Hz, 1 H, 3-H), 3.48 (s, 3 H, O*Me*), 3.55 (ddd, *J* = 9.3, 4.8, 2.2 Hz, 1 H, 5-H), 3.58 (dd, *J* = 9.3, 8.7 Hz, 1 H, 4-H), 3.64–3.66 (m, 2 H, 12-H, 12'-H), 4.04 (dd, *J* = 12.3, 2.2 Hz, 1 H, 6-H), 4.16 (dd, *J* = 12.3, 4.8 Hz, 1 H, 6'-H), 4.26 (d, *J* = 8.7 Hz, 1 H, 1-H), 4.48 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.87 (d, *J* = 10.4 Hz, 1 H, 7-H), 4.94 (dd, *J* = 10.4, 9.4 Hz, 1 H, 8-H), 5.01 (t, *J* = 9.4 Hz, 1 H, 9-H), 5.06 (t, *J* = 9.4 Hz, 1 H, 10-H), 7.08–7.29 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 20.5, 20.5, 20.6, 20.7 (4q, OAc), 52.0 (d, C-2), 56.9 (q, O*Me*), 62.2 (t, C-6), 68.2 (d, C-9), 68.5 (t, C-12), 71.0 (d, C-8), 73.5 (t, C*H*$_2$-Ph), 73.9, 74.8 (2d, C-10, C-11), 74.9 (t, C*H*$_2$-Ph), 75.7 (d, C-5), 76.2 (t, C*H*$_2$-Ph), 79.2, 83.4, 83.8 (3d, C-4, C-7, C-3), 104.0 (d, C-1), 127.6, 127.7, 127.8, 127.9, 128.1, 128.3, 128.4, 128.4 (m, arom. *C*-H), 137.8, 137.8, 137.9 (3q, arom. *C*-CH_2O), 169.3, 169.3, 170.1, 170.6 (4s, OAc).

IR (film): *v* = 3062, 3030, 2920, 1752, 1497, 1367, 1223, 1111, 1042, 752, 700 cm^{-1}.

Anal. calcd for $C_{42}H_{50}O_{14}S$ (810.90): C 62.21, H 6.22, S 3.95; found: C 62.11, H 6.17, S 4.54.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(8,9,10,12-tetra-*O*-acetyl-7-deoxy-*β*-D-galactopyrano)-*β*-D-glucopyranoside (*β-gluco*-47):



47

Nature = Colorless viscous oil (161 mg, 80%).

R_f = 0.08 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = –6.1 (c = 1.07 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.78, 1.88, 1.92, 2.05 (4s, 12 H, OAc), 2.97 (dd, *J* = 10.7, 8.5 Hz, 1 H, 2-H), 3.38 (dt, *J* = 9.7, 3.3 Hz, 1 H, 5-H), 3.42 (dd, *J* = 10.7, 8.5 Hz, 1 H, 3-H), 3.48 (s, 3 H, O*Me*), 3.57 (dd, *J* = 9.7, 8.5 Hz, 1 H, 4-H), 3.63–3.68 (m, 2 H, 6-H, 6'-H), 3.77 (td, *J* = 6.6, 1.3 Hz, 1 H, 11-H), 4.02 (dd, *J* = 11.4, 6.6 Hz, 1 H, 12-H), 4.08 (dd, *J* = 11.4, 6.6 Hz, 1 H, 12'-H), 4.26 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.47 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.51 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.73 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.743(d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.86 (dd, *J* = 10.1, 3.5 Hz, 1 H, 9-H),

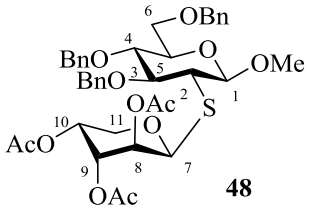
4.88 (d, *J* = 10.1 Hz, 1 H, 7-H), 5.14 (t, *J* = 10.1 Hz, 1 H, 8-H), 5.31 (dd, *J* = 3.5, 1.3 Hz, 1 H, 10-H), 7.07–7.27 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 20.4, 20.5, 20.5, 20.5 (4q, OAc), 51.9 (d, C-2), 56.8 (q, O*Me*), 61.4 (t, C-6), 67.2, 68.3 (2d, C-10, C-8), 68.5 (t, C-12), 71.8 (d, C-9), 73.4 (t, CH_2-Ph), 74.3, 74.8 (2d, C-11, C-5), 74.8, 76.1 (2t, CH_2-Ph), 79.1, 83.6, 84.3 (3d, C-4, C-3, C-7), 103.9 (d, C-1), 127.5, 127.6, 127.7, 127.8, 127.9, 128.2, 128.3 (m, arom. *C*-H), 137.7, 137.8, 137.9 (3q, arom. *C*-CH_2O), 169.4, 169.9, 170.1, 170.2 (4s, OAc).

IR (film): *v* = 3060, 3031, 2934, 1749, 1532, 1369, 1222, 1110, 1051, 751, 701 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{42}H_{50}NaO_{10}S$: 833.2819; found: 833.2813.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(8,9,10-tri-*O*-acetyl-7-deoxy-*β*-D-arabinopyrano) -*β*-D-glucopyranoside (*β-gluco*-48):



48

Nature = Colorless viscous oil (175 mg, 95%).

R_f = 0.07 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +13.5 (c = 1.06 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.98, 2.00, 2.03 (3s, 9 H, OAc), 2.94 (dd, *J* = 11.0, 8.8 Hz, 1 H, 2-H), 3.32 (dd, *J* = 11.0, 8.5 Hz, 1 H, 3-H), 3.37 (ddd, *J* = 9.8, 4.4, 2.2 Hz, 1 H, 5-H), 3.45 (dd, *J* = 12.3, 2.8 Hz, 1 H, 11-H), 3.48 (s, 3 H, O*Me*), 3.56 (dd, *J* = 9.8, 8.5 Hz, 1 H, 4-H), 3.63 (dd, *J* = 10.9, 4.4 Hz, 1 H, 6-H), 3.67 (dd, *J* = 10.9, 2.2 Hz, 1 H, 6'-H), 4.03 (dd, *J* = 12.3, 6.1 Hz, 1 H, 11'-H), 4.20 (d, *J* = 8.8 Hz, 1 H, 1-H), 4.46 (d, *J* = 10.7 Hz, 1 H, CH_2-Ph), 4.46 (d, *J* = 10.5 Hz, 1 H, CH_2-Ph), 4.54 (d, *J* = 12.3 Hz, 2 H, CH_2-Ph), 4.72 (d, *J* = 10.7 Hz, 1 H, CH_2-Ph), 4.89 (d, *J* = 10.5 Hz, 1 H, CH_2-Ph), 5.04 (dd, *J* = 7.3, 3.1 Hz, 1 H, 9-H), 5.08 (dd, *J* = 7.3, 5.9 Hz, 1 H, 8-H), 5.12 (d, *J* = 5.9 Hz, 1 H, 7-H), 5.17 (ddd, *J* = 6.1, 3.1, 2.8 Hz, 1 H, 10-H), 7.07–7.38 (m, 15 H, arom H).

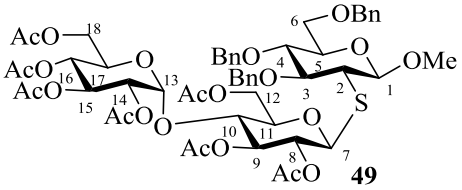
^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 20.6, 20.7, 20.7 (3q, OAc), 51.1 (d, C-2), 57.3 (q, O*Me*), 66.9 (d, C-10), 68.7 (t, C-6), 69.5, 69.5 (2d, C-8, C-9), 73.4 (t, C-11), 73.4 (t, CH_2-Ph), 74.8 (d, C-5), 74.8, 75.8 (2t, CH_2-Ph), 78.9, 82.0, 82.9 (3d, C-4, C-3, C-7), 105.7 (d, C-1), 127.5, 127.6,

127.6, 127.7, 127.8, 127.9, 128.1, 128.2, 128.3 (m, arom. *C*-H), 137.9, 138.0, 138.2 (3q, arom. *C*-CH_2O), 169.3, 169.6, 169.9 (3s, OAc).

IR (film): v = 3477, 3028, 2865, 1745, 1496, 1369, 1213, 1105, 1045, 912, 736, 699 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{39}H_{46}NaO_{12}S$: 761.2608; found: 761.2419.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(8,9,12,14,15,16,18-hepta-*O*-acetyl-7-deoxy-*β*-D-maltopyrano)-*β*-D-glucopyranoside (*β-gluco*-49):



49

Nature = Colorless viscous oil (155 mg, 57%).

R_f = 0.50 (hexane/ethyl acetate 1:1).

$[\alpha]_D^{23}$ = +34.7 (c = 1.07 in $CHCl_3$).

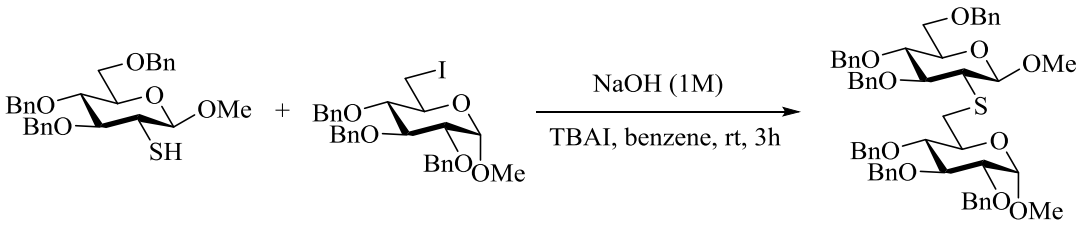
^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.74, 1.90, 1.92, 1.94, 1.98, 2.01, 2.02 (7s, 21 H, OAc), 2.96 (dd, *J* = 10.9, 8.6 Hz, 1 H, 2-H), 3.36–3.39 (m, 1 H, H-17), 3.39 (dd, *J* = 10.9, 8.6 Hz, 1 H, 3-H), 3.49 (s, 3 H, O*Me*), 3.53 (ddd, *J* = 9.8, 4.2, 2.9 Hz, 1 H, 5-H), 3.57 (dd, *J* = 9.8, 8.6 Hz, 1 H, 4-H), 3.63–3.68 (m, 2 H, H-6, H-16), 3.87 (ddd, *J* = 10.4, 3.7, 2.5 Hz, 1 H, 11-H), 3.90 (dd, *J* = 10.4, 8.6 Hz, 1 H, 10-H), 3.96 (dd, *J* = 12.4, 2.9 Hz, 1 H, 6'-H), 3.96 (dd, *J* = 12.0, 2.5 Hz, 1 H, 12-H), 4.15 (dd, *J* = 12.0, 4.4 Hz, 1 H, 18-H), 4.17 (dd, *J* = 12.0, 3.7 Hz, 1 H, 12'-H), 4.26 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.34 (dd, *J* = 12.0, 2.6 Hz, 1 H, 18'-H), 4.47 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.73 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 3.77 (dd, *J* = 10.5, 4.6 Hz, 1 H, 14-H), 4.78 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.90 (d, *J* = 10.5 Hz, 1 H, 7-H), 4.97 (dd, *J* = 10.5, 9.7 Hz, 1 H, 15-H), 5.12 (dd, *J* = 9.4, 8.6 Hz, 1 H, 9-H), 5.28 (dd, *J* = 10.5, 9.4 Hz, 1 H, 8-H), 5.32 (d, *J* = 4.6 Hz, 1 H, 13-H), 7.08–7.27 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 20.4, 20.4, 20.4, 20.4, 20.5, 20.6, 20.7 (7q, OAc), 51.7 (d, C-2), 56.7 (q, O*Me*), 61.4, 63.1 (2t, C-12, C-18), 67.9, 68.4 (2d, C-16, C-15), 68.5 (t, C-6), 69.2, 69.8, 71.9, 72.7 (4d, C-11, C-8, C-14, C-10), 73.4, 74.8 (2t, C*H*$_2$-Ph), 74.8, 75.9 (2d, C-3, C-9), 76.0 (t, C*H*$_2$-Ph), 76.4, 79.2 (2d, C-5, C-4), 83.1 (d, C-17), 83.4, 95.4, 103,9 (3d, C-7, C-13, C-1), 127.5, 127.6, 127.7, 127.8, 128.0, 128.2, 128.3 (m, arom. *C*-H), 137.7, 137.8, 137.9 (3q, arom. *C*-CH_2O), 169.2, 169.5, 169.7, 169.9, 170.3, 170.3, 170.4 (7s, OAc).

IR (film): v = 3452, 3065, 2933, 2368, 1748, 1496, 1368, 1226, 1032, 751, 700 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{54}H_{66}NaO_{22}S$: 1121.3664; found: 1121.3510.

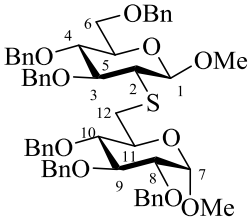
Procedure for the synthesis of the (2→6) linked thiodisaccharide 51.



β-gluco-**16** **50** **51**

The thiol **16** (120 mg, 0.25 mmol) was dissolved in dry benzene (2 mL) at room temperature under nitrogen atmosphere. Tetrabutylammonium iodide (92 mg, 0.25 mmol, 1 equiv) and a solution of sodium hydroxide (1 M, 2 mL) were added and it was allowed to stir for 5 min. Then 6-iodosugar **50** (172 mg, 0.30 mmol, 1.2 equiv) was added to the above solution and stirred for 3 h until TLC showed complete conversion. The reaction mixture was diluted with dichloromethane (30 mL) and extracted with water (25 mL). The aqueous layer was further extracted with dichloromethane (3 X 30 mL). The combined organic layers were washed with brine (25 mL), dried over sodium sulfate, concentrated and purified by silica gel column chromatography (petroleum ether/MTBE 75:25) to afford a thiodisaccharide **51** in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methyl 8,9,10-tri-*O*-benzyl-12-deoxy-*α*-D-gluco pyranosyl)-*β*-D-glucopyranoside (*β-gluco*-51):



51

Nature = Colorless viscous oil (205 mg, 88%).

R_f = 0.42 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +33.4 (c = 0.99 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.80 (dd, *J* = 13.5, 7.9 Hz, 1 H, 12-H, S*CH*$_2$), 2.84 (dd, *J* = 10.7, 8.8 Hz, 1 H, 2-H), 3.15 (dd, *J* = 13.5, 2.8 Hz, 1 H, 12'-H, S*CH*$_2$), 3.21 (s, 3 H, O*Me*), 3.26 (dd, *J* = 10.7, 8.8 Hz, 1 H, 3-H), 3.34 (ddd, *J* = 9.8, 4.5, 2.2 Hz, 1 H, 5-H), 3.34 (dd, *J* = 9.8, 8.7 Hz, 1 H, 9-H), 3.38 (dd, *J* = 9.8, 4.1 Hz, 1 H, 8-H), 3.40 (s, 3 H, O*Me*), 3.52 (dd, *J* = 9.8, 8.8 Hz, 1 H, 4-H), 3.61 (dd, *J* = 10.7, 4.5 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.7, 2.2 Hz, 1 H, 6'-H), 3.74 (ddd, *J* = 9.8, 7.9, 2.8 Hz, 1 H, 11-H), 3.87 (dd, *J* = 9.8, 8.7 Hz, 1 H, 10-H), 4.13 (d, *J* = 8.8 Hz, 1 H, 1-

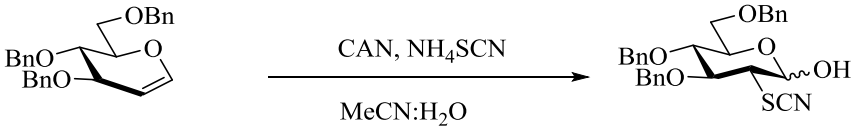
H), 4.45 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 4.1 Hz, 1 H, 7-H), 4.46 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.53 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.70 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.83 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.88 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 7.06–7.30 (m, 30 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 34.5 (t, C-12, S*CH*$_2$), 52.9 (d, C-2), 55.0, 56.9 (2q, O*Me*), 68.8 (t, C-6), 70.3 (d, C-11), 73.2, 73.4 (2t, C*H*$_2$-Ph), 74.7 (d, C-5), 74.8, 75.0, 75.6, 76.0 (4t, C*H*$_2$-Ph), 79.0, 80.0, 80.6, 81.8, 83.1 (5d, C-4, C-8, C-9, C-10, C-3), 97.7, 106.0 (2d, C-7, C-1), 127.5, 127.5, 127.7, 127.7, 127.8, 127.9, 128.0, 128.3, 128.3, 128.3 (m, arom. *C*-H), 138.9, 138.0, 138.1, 138.1, 138.2, 138.7 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3479, 3060, 2906, 1603, 1496, 1453, 1358, 1207, 1046, 735, 969 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{56}H_{62}NaO_{10}S$: 949.3961; found: 949.4015.

Procedure for the trapping of oxocarbenium ion by water.



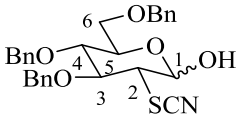
glucal-**3a** **52** (*α*/*β* = 5:1)

To a stirred solution of glucal in **3a** (416 mg, 1 mmol) in acetonitrile/water (7:3, 5 mL) was added ammonium thiocyanate (304 mg, 4 mmol, 4 equiv). A solution of CAN (2.19 g, 4 mmol, 4 equiv) in acetonitrile (15 mL) was added dropwise within 1 h at room temperature and it was stirred for additional 30 min. Upon completion, the solvents were removed *in vacuo* and a crude residue was purified by silica gel column chromatography to afford the 2-thiocyanate **52** (181 mg, 37%) in pure form.

3,4,6-Tri-*O*-benzyl-2-deoxy-2-thiocyanato-*α*/*β*-D-glucopyranoside (*α*/*β*-*gluco*-52):

Nature = White solid (181 mg, 37%).

R_f = 0.19 (hexane/ethyl acetate 8:2).



52

$[\alpha]_D^{23}$ = +70.2 (c = 1.17 in $CHCl_3$).

m.p. = 114–115 °C.

(5:1 mixture of *α/β* anomers) ^{1}H NMR (500 MHz, $CDCl_3$) (*major*, *α*-OH): δ = 3.22 (dd, *J* = 10.7, 3.4 Hz, 1 H, 2-H), 3.46 (dd, *J* = 10.1, 8.8 Hz, 1 H, 4-H), 3.49 (dd, *J* = 10.7, 5.0 Hz, 1 H, 6-H), 3.52 (dd, *J* = 10.7, 2.5 Hz, 1 H, 6'-H), 3.94 (dd, *J* = 10.7, 8.8 Hz, 1 H, 3-H), 4.02 (ddd, *J* = 10.1, 5.0, 2.2 Hz, 1 H, 5-H), 4.70 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.80 (d, *J* = 10.4 Hz, 1 H, C*H*$_2$-Ph), 4.84 (d, *J* = 10.4 Hz, 1 H, C*H*$_2$-Ph), 4.40 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.40 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 5.29 (d, *J* = 3.4 Hz, 1 H, 1-H), 7.05–7.32 (m, 15 H, arom H); (*minor*, *β*-OH): δ = 2.80 (dd, *J* = 10.7, 8.5 Hz, 1 H, 2-H), 3.43 (ddd, *J* = 9.8, 5.4, 1.9 Hz, 1 H, 5-H), 3.59 (dd, *J* = 10.4, 1.9 Hz, 1 H, 6-H), 3.62 (dd, *J* = 10.7, 8.5 Hz, 1 H, 3-H), 6.67 (dd, *J* = 8.5 Hz, 1 H, 1-H).

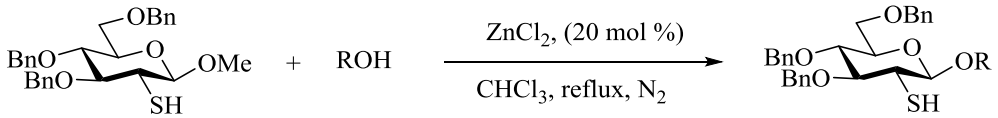
^{13}C APT NMR (125 MHz, $CDCl_3$) (*major, α*-OH) δ = 53.2 (d, C-2), 68.3 (t, C-6), 70.6 (d, C-5), 73.3, 75.0, 76.2 (3t, C*H*$_2$-Ph), 79.7, 79.8 (2d, C-4, C-3), 92.2 (d, C-1), 111.8 (q, SCN), 127.8, 127.9, 128.0, 128.0, 128.2, 128.4 (m, arom. *C*-H), 137.2, 137.3, 137.4 (3q, arom. *C*-CH_2O); (*minor, β*-OH) δ = 54.2 (d, C-2), 68.1 (t, C-6), 73.4, 75.0 (2t, C*H*$_2$-Ph), 79.2, 81.2 (2d, C-5, C-3), 95.3 (d, C-1), 110.1 (q, SCN), 137.2, 137.2, 137.3 (3q, arom. *C*-CH_2O)

IR (film): 3336, 3087, 2853, 2156, 1454, 1136, 1094, 1030, 772, 732, 693 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{27}H_{31}NO_5S$: 492.1845; found: 492.1816.

Anal. calcd for $C_{28}H_{29}NO_5S$ (491.60): C 68.41, H 5.95, N 2.85, S 6.52; found: C 68.11, H 5.94, N 2.85, S 7.04.

General procedure for the zinc chloride mediated transformations of the methyl glycosides to alkyl glycosides.



β-gluco-**16** R = Bn, Et, Oct **54–56** (selectively *β*)

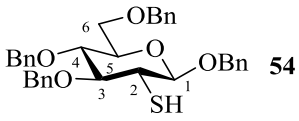
Zinc chloride (14 mg, 20 mol %) was added to a solution of the thiol **16** (240 mg, 0.50 mmol) and appropriate alcohol (2.5 mmol, 5 equiv) in chloroform (3 mL) under nitrogen atmosphere. The resulting reaction mixture was heated under reflux (3–7 h) until TLC showed complete conversion of the starting material. The solvent was removed *in vacuo* and the crude residue was purified by silica gel column chromatography (petroleum ether/MTBE 85:15) to afford thiols **54**–**56** in analytically pure form.

1,3,4,6-Tetra-*O*-benzyl-2-deoxy-2-thio-*β*-D-glucopyranoside (*β-gluco*-54):

Nature = Colorless viscous oil (230 mg, 83%).

R_f = 0.41 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{24}$ = +9.8 (c = 0.96 in $CHCl_3$).



54

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.92 (d, *J* = 3.1 Hz, 1 H, S*H*), 3.06 (ddd, *J* = 10.7, 8.8, 3.1 Hz, 1 H, 2-H), 3.35 (dd, *J* = 10.7, 8.8 Hz, 1 H, 3-H), 3.39 (ddd, *J* = 9.8, 4.0, 2.8 Hz, 1 H, 5-H), 3.55 (dd, *J* = 9.8, 8.8 Hz, 1 H, 4-H), 3.64 (dd, *J* = 10.9, 4.0 Hz, 1 H, 6-H), 3.67 (dd, *J* = 10.9, 2.8 Hz, 1 H, 6'-H), 4.26 (d, *J* = 8.8 Hz, 1 H, 1-H), 4.46 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 11.9 Hz, 1 H, C*H*$_2$-Ph), 4.70 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.82 (d, *J* = 11.9 Hz, 1 H, C*H*$_2$-Ph), 7.08–7.30 (m, 20 H, arom H).

^{13}C APT NMR (125 MHz, $CDCl_3$): δ = 46.1 (d, C-2), 68.7 (t, C-6), 70.9, 73.4, 74.7 (3t, C*H*$_2$-Ph), 75.5 (d, C-3), 75.3 (t, C*H*$_2$-Ph), 78.9, 84.8 (2d, C-4, C-5), 102.5 (d, C-1), 127.6, 127.7, 127.7, 127.8, 127.8, 127.9, 128.1, 128.3, 128.3, 128.3 (m, arom. *C*-H), 137.0, 137.9, 137.9, 138.0 (4q, arom. *C*-CH_2O).

IR (film): *v* = 3087, 3031, 2866, 2579, 1598, 1497, 1454, 1359, 1115, 1050, 738, 698 cm^{-1}.

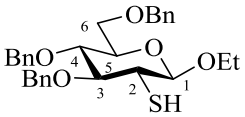
HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{34}H_{37}O_5S$: 557.2362; found: 557.2357.

Anal. calcd for $C_{34}H_{36}O_5S$ (556.71): C 73.35, H 6.52, S 5.76; found: C 73.21, H 6.62, S 6.08.

Ethyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*β*-D-glucopyranoside (*β-gluco*-55):

Nature = White solid (190 mg, 77%).

R_f = 0.41 (hexane/ethyl acetate 8:2).



55

$[\alpha]_D^{23}$ = +11.2 (c = 1.07 in $CHCl_3$).

m.p. = 115–116 °C

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.15 (t, *J* = 7.0 Hz, 3 H, CH_2*Me*), 1.94 (d, *J* = 3.2 Hz, 1 H, S*H*), 2.98 (ddd, *J* = 10.7, 8.5, 3.2 Hz, 1 H, 2-H), 3.36 (dd, *J* = 10.7, 8.8 Hz, 1 H, 3-H), 3.39 (ddd, *J* = 9.7, 7.0, 2.5 Hz, 1 H, 5-H), 3.49 (dd, *J* = 13.8, 9.7 Hz, 1 H, 6-H), 3.50 (dd, *J* = 9.7, 8.8 Hz, 1 H, 4-H), 3.62 (q, *J* = 7.0 Hz, 2 H, OC*H*$_2$), 3.85 (dd, *J* = 13.8, 7.0 Hz, 1 H, 6'-H), 4.18 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.44 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.51 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.76 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 7.07–7.29 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 15.0 (q, *Me*), 46.1 (d, C-2), 65.3 (t, C-6), 68.7 (t, O-*C*H_2), 73.4, 74.7 (2t, C*H*$_2$-Ph), 75.1 (d, C-4), 75.3 (t, C*H*$_2$-Ph), 78.9, 84.7 (2d, C-5, C-3), 103.5 (d, C-1), 127.5, 127.6, 127.7, 127.7, 127.9, 128.2, 128.3 (m, arom. *C*-H), 137.8, 137.8, 138.0 (3q, arom. *C*-CH_2O).

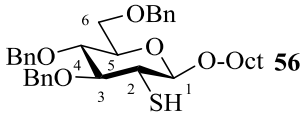
IR (film): *v* = 3084, 3063, 2868, 2577, 1953, 1496, 1358, 1117, 1086, 1048, 740, 700 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{29}H_{35}O_5S$: 495.2205; found: 495.2218.

Octyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-*β*-D-glucopyranoside (*β-gluco*-56):

Nature = White solid (240 mg, 81%).

R_f = 0.76 (hexane/ethyl acetate 8:2).



56

$[\alpha]_D^{23}$ = +12.7 (c = 1.18 in $CHCl_3$).

m.p. = 38–39 °C

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.79 (t, *J* = 7.0 Hz, 3 H, CH_2*Me*), 1.14–1.57 (m, 12 H, –C*H*$_2$–), 1.94 (d, *J* = 2.8 Hz, 1 H, S*H*), 3.00 (ddd, *J* = 10.8, 8.5, 2.8 Hz, 1 H, 2-H), 3.37 (dd, *J* = 10.8, 8.8 Hz, 1 H, 3-H), 3.40–3.43 (m, 1 H, 6-H), 3.40 (ddd, *J* = 9.8, 6.6, 2.8 Hz, 1 H, 5-H), 3.53 (dd, *J* = 9.8, 8.8 Hz, 1 H, 4-H), 3.63 (q, *J* = 7.0 Hz, 2 H, OC*H*$_2$), 3.80 (dd, *J* = 13.2, 6.6 Hz, 1 H, 6'-H),

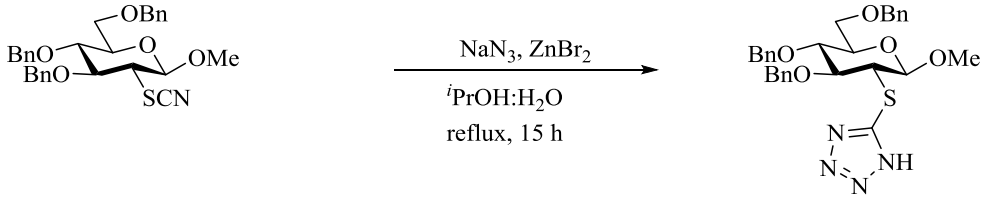
4.17 (d, *J* = 8.4 Hz, 1 H, 1-H), 4.45 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.70 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.77 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 7.08–7.29 (m, 15 H, arom H).

^{13}C APT NMR (125 MHz, $CDCl_3$): δ = 14.0 (q, *Me*), 22.5, 25.9, 29.1, 29.2, 29.4, 31.7 (6t, *C*H$_2$), 46.2 (d, C-2), 68.7 (t, O-*C*H$_2$), 68.9 (t, C-6), 73.4, 74.7 (2t, C*H*$_2$-Ph), 75.1 (d, C-5), 75.2 (t, C*H*$_2$-Ph), 79.0, 84.7 (2d, C-4, C-3), 103.7 (d, C-1), 127.5, 127.6, 127.7, 127.7, 127.7, 127.9, 128.4, 128.3 (m, arom. *C*-H), 137.8, 137.9, 138.0 (3q, arom. *C*-CH$_2$O).

IR (film): *v* = 3087, 3031, 2926, 2857, 2579, 1727, 1496, 1360, 1116, 1087, 1050, 739, 699 cm^{-1}.

Anal. calcd for $C_{35}H_{46}O_5S$ (578.80): C 72.63, H 8.01, S 5.54; found: C 72.36, H 8.41, S 5.83.

Procedure for the (3 + 2) cycloaddition between the 2-thiocyanate 4a and sodium azide.



β-gluco-**4a** **59**

To a stirred solution of 2-thiocyanate **4a** (253 mg, 0.5 mmol) in isopropanol/water (1:1, 10 mL) was added sodium azide (65 mg, 0.55 mmol, 1.1 equiv) followed by zinc bromide (111 mg, 0.5 mmol, 1 equiv). The resulting reaction mixture was heated under reflux for 15 h until TLC showed complete conversion of the starting material. The solvents were removed under reduced pressure and the crude residue was purified by silica gel column chromatography to afford a thiotetrazole **59** in analytically pure form.

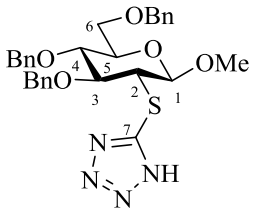
Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(tetrazolyl)-*β*-D-glucopyranoside (*β-gluco*-59):

Nature = White solid (233 mg, 85%).

R_f = 0.02 (hexane/ethyl acetate 2:8).

$[\alpha]_D^{24}$ = +6.5 (c = 1.18 in $CHCl_3$).

m.p. = 97–98 °C.



59

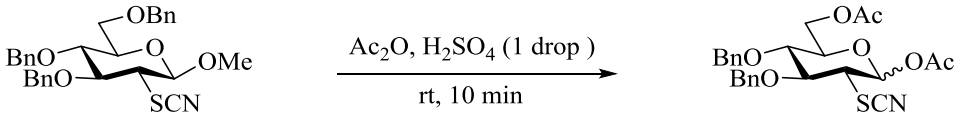
^{1}H NMR (500 MHz, $CDCl_3$): δ = 3.31 (s, 3 H, O*Me*), 3.32 (dd, *J* = 10.8, 8.8 Hz, 1 H, 2-H), 3.47 (dt, *J* = 6.4, 3.4 Hz, 1 H, 5-H), 3.62–3.67 (m, 3 H, H-4, H-6, H-6'), 3.71 (dd, *J* = 10.8, 8.7 Hz, 1 H, 3-H), 4.49 (d, *J* = 8.8 Hz, 1 H, 1-H), 4.35 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.43 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.68 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.71 (s, 2 H, C*H*$_2$-Ph), 7.03–7.20 (m, 15 H, arom H), 10.11 (s, 1H, N*H*).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 54.0 (d, C-2), 57.3 (q, O*Me*), 68.0 (t, C-6), 74.5 (d, C-5), 74.8, 76.0 (2t, C*H*$_2$-Ph), 79.2, 81.0 (2d, C-4, C-3), 103.0 (d, C-1), 127.6, 127.7, 127.8, 127.9, 127.9, 128.1, 128.3, 128.3 (m, arom. *C*-H), 137.2, 137.2, 137.5 (3q, arom. *C*-CH_2O), 153.0 (s, C-7, S*C*).

IR (film): *v* = 3087, 3063, 2908, 2726, 1955, 1809, 1496, 1454, 1210, 1108, 1049, 744, 699 cm^{-1}.

Anal. calcd for $C_{29}H_{32}N_4O_5S$ (548.65): C 63.49, H 5.88, N 10.21, S 5.84; found: C 63.61, H 5.85, N 9.69, S 5.88.

Procedure for the trapping of anomeric center by water.



β-gluco-**4a** — **60** (*α*/*β* 10:2.3)

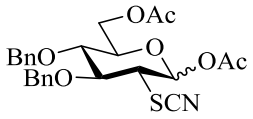
To a stirred solution of thiocyanate **4a** (253 mg, 0.25 mmol) in acetic anhydride (5 mL) was added a drop of sulfuric acid under nitrogen atmosphere. It was then stirred for 10 min until the TLC showed complete conversion of the starting material. Then the reaction mixture was diluted with dichloromethane (25 mL) and extracted with water (25 mL). The aqueous phase was further extracted with dichloromethane (2 x 25 mL). The combined organic phases were washed with saturated aqueous $NaHCO_3$, brine, dried over sodium sulfate and purified by column chromatography to afford the 1,6-diacetyl sugar **60** in pure form.

3,4-Di-*O*-benzyl-1,6-di-*O*-acetyl-2-deoxy-2-thiocyanato-*α*/*β*-D-glucopyranoside (*α*/*β*-*gluco*-60):

Nature = Colorless viscous liquid (190 mg, 78%).

R_f = 0.29 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +148.8 (c = 0.91 in $CHCl_3$).



60
(*α*:*β* 10:2.3)

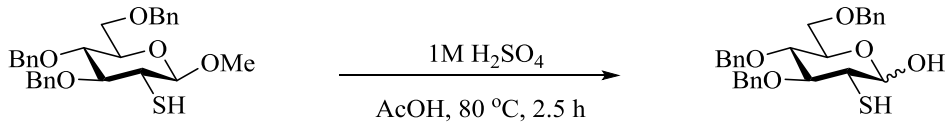
(1:0.23 mixture of *α*/*β* anomers) ^{1}H NMR (600 MHz, $CDCl_3$) (*major*, *α*-OAc): δ = 1.94, 2.13 (2s, 6 H, O*Ac*), 3.14 (dd, *J* = 10.9, 3.4 Hz, 1 H, 2-H), 3.61 (dd, *J* = 10.2, 8.6 Hz, 1 H, 4-H), 3.90 (dt, *J* = 10.2, 3.4 Hz, 1 H, 5-H), 4.02 (dd, *J* = 10.9, 8.6 Hz, 1 H, 3-H), 4.16–4.17 (m, 2 H, 6-H, 6'-H), 4.52 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.79 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.88 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.91 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 6.24 (d, *J* = 3.4 Hz, 1 H, 1-H), 7.15–7.33 (m, 10 H, arom H); (*minor*, *β*-OAc): δ = 1.94, 2.09 (2s, 6 H, O*Ac*), 3.07 (dd, *J* = 10.6, 9.0 Hz, 1 H, 2-H), 3.57 (dd, *J* = 10.1, 8.2 Hz, 1 H, 4-H), 3.60–3.63 (m, 1 H, 5-H), 3.69 (dd, *J* = 10.6, 8.2 Hz, 1 H, 3-H), 4.15 (dd, *J* = 12.1, 4.4 Hz, 1 H, 6-H), 4.24 (dd, *J* = 12.1, 1.9 Hz, 1 H, 6'-H), 4.52 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.77 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.81 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.85 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 5.68 (d, *J* = 9.0 Hz, 1 H, 1-H), 7.15–7.33 (m, 10 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$) (*major*, *α*-OAc): δ = 20.6, 20.7 (2q, *OAc*), 50.4 (d, C-2), 61.9 (t, C-6), 71.3 (d, C-5), 75.2, 76.2 (2t, C*H*$_2$-Ph), 78.6, 79.0 (2d, C-4, C-3), 91.3 (d, C-1), 109.7 (q, SCN), 127.8, 127.9, 127.9, 128.1, 128.1, 128.4, 128.5 (m, arom. *C*-H), 136.9, 137.1 (2q, arom. *C*-CH_2O), 168.4, 170.3 (2s, OAc); (*minor*, *β*-OAc): δ = 20.5, 20.6 (2q, *OAc*), 52.0 (d, C-2), 62.0 (t, C-6), 73.6 (d, C-4), 75.0, 76.2 (2t, C*H*$_2$-Ph), 78.5, 80.8 (2d, C-5, C-3), 92.2 (d, C-1), 109.1 (q, SCN), 127.8, 127.9, 127.9, 128.1, 128.1, 128.4, 128.5 (m, arom. *C*-H), 136.8, 136.9 (2q, arom. *C*-CH_2O), 168.3, 170.3 (2s, OAc).

IR (film): 3465, 2917, 2156, 2016, 1740, 1367, 1211, 1007, 927, 744, 698 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{25}H_{28}NO_7S$: 486.1586; found: 486.1552.

Procedure for the reaction of methyl glycosides to reducing sugars.



β-*gluco*-**16** **61**, 70%

To a stirred solution of thiol **16** (120 mg, 0.25 mmol) in acetic acid (1 mL) was added sulfuric acid (1M, 0.5 mL) under nitrogen atmosphere. It was then heated at 80 °C for 2.5 h until the TLC showed complete conversion of the starting material. Then the reaction mixture was diluted with dichloromethane (25 mL) and extracted with water (25 mL). The aqueous phase was further extracted with dichloromethane (2 x 25 mL). The combined organic phases were washed with saturated aqueous $NaHCO_3$, brine, dried over sodium sulfate and purified by column chromatography to afford the reducing sugar **61** in pure form.

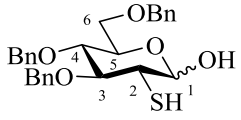
3,4,6-Tri-*O*-benzyl-2-deoxy-2-thio-*α*/*β*-D-glucopyranoside (*α*/*β*-*gluco*-61):

Nature = White solid (80 mg, 69%).

R_f = 0.17 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +91.2 (c = 1.23 in $CHCl_3$).

m.p. = 116–117 °C.



61

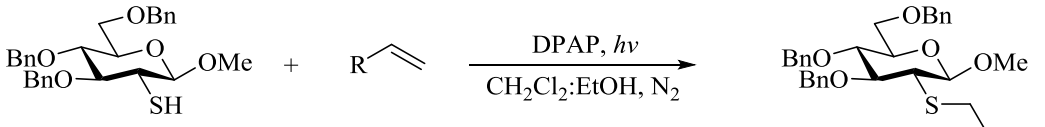
(1:0.26 mixture of *α*/*β* anomers) ^{1}H NMR (600 MHz, $CDCl_3$) (*major*, *α*-OH): δ = 1.81 (d, *J* = 9.4 Hz, 1 H, S*H*), 2.85 (ddd, *J* = 10.9, 9.4, 3.4 Hz, 1 H, 2-H), 3.40 (dd, *J* = 10.2, 9.0 Hz, 1 H, 4-H), 3.52–3.56 (m, 2 H, 6-H, 6'-H), 3.71 (dd, *J* = 10.9, 9.0 Hz, 1 H, 3-H), 3.75 (s, 1 H, O*H*), 4.04 (ddd, *J* = 10.2, 4.5, 2.6 Hz, 1 H, 5-H), 4.41 (d, *J* = 11.2 Hz, 1 H, CH_2-Ph), 4.42 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.49 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.74 (d, *J* = 11.2 Hz, 1 H, CH_2-Ph), 4.77 (d, *J* = 10.4 Hz, 1 H, CH_2-Ph), 4.91 (d, *J* = 10.4 Hz, 1 H, CH_2-Ph), 5.20 (d, *J* = 3.4 Hz, 1 H, 1-H), 7.15–7.33 (m, 15 H, arom H); (*minor*, *β*-OH): δ = 1.90 (d, *J* = 4.2 Hz, 1 H, S*H*), 2.92 (ddd, *J* = 10.9, 8.7, 4.2 Hz, 1 H, 2-H), 3.33 (dd, *J* = 10.9, 8.3 Hz, 1 H, 3-H), 3.44 (ddd, *J* = 9.8, 4.9, 1.9 Hz, 1 H, 5-H), 3.48 (dd, *J* = 9.8, 8.3 Hz, 1 H, 4-H), 3.48–3.52 (m, 1 H, 6-H), 3.61 (dd, *J* = 10.5, 1.9 Hz, 1 H, 6'-H), 4.42 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 4.45 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.46 (d, *J* = 11.1 Hz, 1 H, CH_2-Ph), 4.47 (d, *J* = 11.1 Hz, 1 H, CH_2-Ph), 4.50 (d, *J* = 12.4 Hz, 1 H, CH_2-Ph), 4.52 (d, *J* = 8.7 Hz, 1 H, 1-H), 4.70 (d, *J* = 10.9 Hz, 1 H, CH_2-Ph), 7.15–7.33 (m, 15 H, arom H).

^{13}C APT NMR (150 MHz, $CDCl_3$) (*major*, α-OH): δ = 47.6 (d, C-2), 68.6 (t, C-6), 70.7 (d, C-5), 73.4, 74.9, 76.2 (3t, CH_2-Ph), 79.4, 82.8 (2d, C-4, C-3), 94.1 (d, C-1), 127.7, 127.8, 127.8, 127.9, 128.0, 128.0, 128.1, 128.4, 128.4, 128.4 (m, arom. *C*-H), 137.6, 137.9, 138.2 (3q, arom. *C*-CH_2O); (*minor*, β-OH): δ = 54.2 (d, C-2), 68.1 (t, C-6), 73.5 (t, CH_2-Ph), 74.8 (d, C-4), 74.8, 75.6 (2t, CH_2-Ph), 78.8, 84.7 (2d, C-5, C-3), 98.0 (d, C-1), 137.5, 137.6, 137.8 (3q, arom. *C*-CH_2O)

IR (film): 3396, 3028, 2865, 1726, 1453, 1209, 1117, 2034, 998, 745, 693 cm^{-1}.

Anal. calcd for $C_{27}H_{30}O_5S$ (466.59): C 69.50, H 6.48, S 6.87; found: C 69.53, H 6.73, S 6.74.

General procedure for the photochemical addition of 2-thiol 16 to terminal alkenes.



16 **63** R = OAc, TMS **64 & 65**

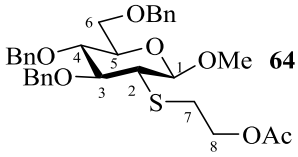
To a solution of thiol **16** (120 mg, 0.25 mmol) and the appropriate terminal alkene **63** (1.25 mmol, 5 equiv) in dichloromethane/ethanol (1:4, 1 mL) was added 2,2-dimethoxy-2-phenylacetophenone (DPAP, 13 mg, 20 mol %). The resulting reaction mixture was degassed under a flow of nitrogen for 10 min and irradiated under UV light until TLC showed complete conversion of starting material. The solvents were removed *in vacuo* and the crude residue was purified by silica gel column chromatography to afford the addition products **64** & **65** in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(ethylacetato)-*β*-D-glucopyranoside (*β-gluco*-64):

Nature = Colorless viscous oil (232 mg, 82%).

R_f = 0.31 (hexane/ethyl acetate 2:8).

$[\alpha]_D^{24}$ = +38.6 (c = 0.97 in $CHCl_3$).



64

^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.91 (s, 3 H, CO*Me*), 2.70 (dd, *J* = 11.3, 8.5 Hz, 1 H, 2-H), 2.80 (dt, *J* = 13.6, 6.8 Hz, 1 H, 7-H, SCH_2), 2.98 (dt, *J* = 13.6, 9.8 Hz, 1 H, 7'-H, SCH_2), 3.26 (dd, *J* = 11.3, 8.6 Hz, 1 H, 3-H), 3.36 (ddd, *J* = 9.8, 4.6, 1.9 Hz, 1 H, 5-H), 3.47 (s, 3 H, O*Me*), 3.53 (dd, *J* = 9.8, 8.6 Hz, 1 H, 4-H), 3.61 (dd, *J* = 10.9, 4.6 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.9, 1.9 Hz, 1 H, 6'-H), 4.15 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.15 (4.14–4.17, m, 2 H, 8-H, 8'-H, OCH_2), 4.45 (d, *J* = 12.0

Hz, 1 H, CH_2-Ph), 4.46 (d, J = 10.8 Hz, 1 H, CH_2-Ph), 4.53 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.71 (d, J = 10.5 Hz, 1 H, CH_2-Ph), 4.72 (d, J = 10.8 Hz, 1 H, CH_2-Ph), 4.85 (d, J = 10.5 Hz, 1 H, CH_2-Ph), 7.07–7.31 (m, 15 H, arom H).

^{13}C APT NMR (150 MHz, $CDCl_3$): δ = 20.7 (q, CO*Me*), 31.3 (t, C-7, SCH_2), 53.1 (d, C-2), 57.1 (q, O*Me*), 63.6 (t, C-8, OCH_2), 68.6 (t, C-6), 73.4 (t, CH_2-Ph), 74.6 (d, C-5), 74.8 (t, CH_2-Ph), 76.2 (t, CH_2-Ph), 79.0, 82.9 (2d, C-4, C-3), 105.8 (d, C-1), 127.5, 127.6, 127.6, 127.7, 127.7, 127.8 (m, arom. *C*-H), 137.9, 138.0, 138.1 (3q, arom. *C*-CH_2O), 170.7 (O*CO*Me).

IR (film): v = 3060, 3030, 2863, 1938, 1496, 1359, 1229, 1108, 1046, 937, 697 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{32}H_{38}NaO_7S$: 589.2236; found: 589.2223.

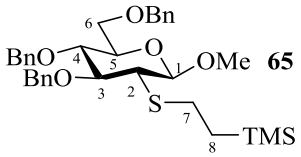
Anal. calcd for $C_{32}H_{38}O_7S$ (566.70): C 67.82, H 6.76, S 5.66; found: C 67.58, H 6.26, S 5.88.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(ethyltrimethylsilano)-*β*-D-glucopyranoside (*β*-*gluco*-65):

Nature = Colorless viscous oil (97 mg, 68%).

R_f = 0.58 (hexane/ethyl acetate 2:8).

$[\alpha]_D^{23}$ = –7.1 (c = 1.12 in $CHCl_3$).



65

^{1}H NMR (600 MHz, $CDCl_3$): δ = 0.00 (s, 9 H, SiMe_3), 0.86 (ddd, J = 14.3, 12.8, 4.9 Hz, 1 H, 8-H, SiCH_2), 0.97 (ddd, J = 14.3, 12.8, 4.9 Hz, 1 H, 8'-H, SiCH_2), 2.78 (ddd, J = 17.2, 12.8, 4.9 Hz, 1 H, 7-H, SCH_2), 2.79 (dd, J = 10.9, 8.6 Hz, 1 H, 2-H), 2.83 (ddd, J = 17.2, 12.8, 4.9 Hz, 1 H, 7'-H, SCH_2), 3.42 (dd, J = 10.9, 8.6 Hz, 1 H, 3-H), 3.47 (ddd, J = 9.8, 4.5, 2.2 Hz, 1 H, 5-H), 3.57 (s, 3 H, O*Me*), 3.63 (dd, J = 9.8, 8.6 Hz, 1 H, 4-H), 3.72 (dd, J = 10.9, 4.5 Hz, 1 H, 6-H), 3.76 (dd, J = 10.9, 2.2 Hz, 1 H, 6'-H), 4.25 (d, J = 8.6 Hz, 1 H, 1-H), 4.56 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.57 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.64 (d, J = 12.0 Hz, 1 H, CH_2-Ph), 4.82 (d, J = 10.9 Hz, 1 H, CH_2-Ph), 4.83 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 4.99 (d, J = 11.0 Hz, 1 H, CH_2-Ph), 7.18–7.42 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = –1.9 (3q, SiMe_3), 17.7 (t, C-8, SiCH_2), 28.9 (t, C-7, SCH_2), 52.4 (d, C-2), 57.0 (q, O*Me*), 68.9 (t, C-6), 73.4 (t, CH_2-Ph), 74.8 (d, C-5), 74.8, 76.1 (2t, CH_2-

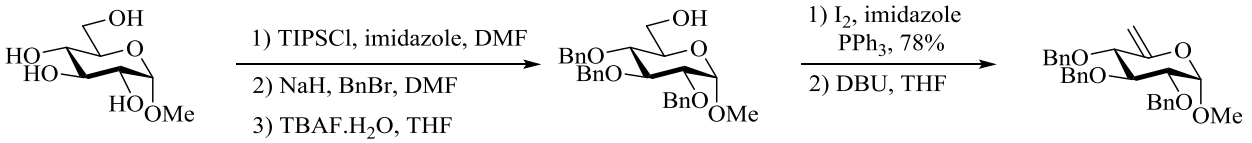
Ph), 79.1, 83.4 (2d, C-4, C-3), 105.7 (d, C-1), 127.5, 127.6, 127.6, 127.8, 127.9, 128.2, 128.3 (m, arom. *C*-H), 138.0, 138.1, 138.3 (3q, arom. *C*-CH_2O).

IR (film): ν = 3431, 3030, 2950, 1952, 1496, 1453, 1248, 1106, 1047, 836, 736, 696 cm^{-1}.

Anal. calcd for $C_{33}H_{44}O_5SSi$ (580.85): C 68.24, H 7.64, S 5.52; found: C 67.72, H 8.70, S 5.58.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{33}H_{45}O_5SSi$: 581.2757; found: 581.2677.

Procedure for the synthesis of the *exo*-glycal 63e.[65]



66 **67**, 95% **63e**, 76%

(1st Step)[65a]: To a solution of methyl α-D-glucopyranoside **66** (3.66 g, 18.85 mmol) and imidazole (3.86 g, 56.55 mmol, 3 equiv) in dimethylformamide (30 mL), TIPSCl (4.43 mL, 20.70 mmol, 1.1 equiv) was added dropwise over a period of 15 min at 0 °C. It was stirred at ambient temperature for 24 h. After completion, the reaction mixture was diluted with water (100 mL) and extracted with dichloromethane (3 X 50 mL). The combined organic layers were washed with brine, dried over sodium sulfate, concentrated and placed under vacuum for 1 h. For the next step, benzyl bromide (11.2 mL, 94.28 mmol, 5 equiv) was added to a solution of the above crude reaction mixture in dry dimethylformamide (100 mL) at 0 °C. At this temperature, sodium hydride (60% dispersion in mineral oil, 3.77 g, 94.28 mmol, 5 equiv) was added portion wise under nitrogen atmosphere and stirred at ambient temperature for 12 h. Upon completion, the reaction mixture was quenched by a slow addition of methanol and ice-water (50 mL) at 0 °C and extracted with diethyl ether (3 X 100 mL). The combined organic layers were washed with brine, dried over sodium sulfate, concentrated and used for the next step without purification. To a solution of the above crude reaction mixture in tetrahydrofuran (20 mL), TBAF·H_2O (12 g, 36.03 mmol, 2 equiv) was added and stirred for 12 h. Upon completion, the reaction mixture was diluted with water (100 mL) and extracted with ethyl acetate (3 X 100 mL). The combined organic layers were washed with brine, dried over sodium sulfate, concentrated and purified by column chromatography to afford methyl 2,3,4-tri-*O*-benzyl-α-D-glucopyranoside **67** (8.32 g, 95%) as colorless viscous liquid; Lit.[65a]: (Yield = 99%).

(2nd Step)[65b]: To a solution of methyl 2,3,4-tri-*O*-benzyl-α-D-glucopyranoside (6.70 g, 15 mmol) in toluene (100 mL) was added triphenylphosphine (7.87 g, 30 mmol, 2 equiv), imidazole (5.10 g, 75 mmol, 5 equiv) and iodine (3.80 g, 30 mmol, 2 equiv). The resulting reaction mixture was stirred at 80 °C for 3 h until TLC showed complete conversion of starting material. The solvent was removed *in vacuo* and the resulting residue was rinsed with ethyl acetate (3 X 50 mL), concentrated and purified by silica gel column chromatography (petroleum ether/MTBE 85:15) to afford methyl 6-deoxy-6-iodo-2,3,4-tri-*O*-benzyl-α-D-glucopyranoside (6.68 g, 78%) as pale yellow solid; Lit.[65b]: (Yield = 81%).

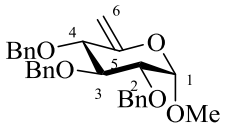
(3rd Step)[65b]: To a solution of 6-deoxy-6-iodo-2,3,4-tri-*O*-benzyl-α-D-glucopyranoside (2.87 g, 5 mmol) in dry dimethylformamide (75 mL) was added 1,8-diazabicyclo[5.4.0]undec-7-ene (1.52 g, 10 mmol, 2 equiv) under argon atmosphere. The resulting reaction mixture was stirred at 80 °C for 15 h. Upon completion, it was then diluted with ethyl acetate (100 mL) and washed with saturated aqueous $NaHCO_3$ (3 X 50 mL). The organic phase was extracted with water (2 X 50 mL), dried over sodium sulfate, concentrated and purified by silica gel column chromatography (petroleum ether/MTBE 80:20) to afford *exo*-glycal **63e** (1.69 g, 76%) as viscous liquid; Lit.[65b]: (Yield = 71%).

Methyl 2,3,4-tri-*O*-benzyl-6-deoxy-*a*-D-glucohept-5-enitol (*exo-glycal*-63e):

Nature = Colorless viscous oil (1.69 g, 76%).

R_f = 0.54 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +6.2 (c = 0.73 in $CHCl_3$); Lit.[65c]: +2.0 (c = 1 in CH_2Cl_2).



63e

^{1}H NMR (300 MHz, $CDCl_3$): δ = 3.33 (s, 3 H, O*Me*), 3.52 (dd, *J* = 9.0, 3.4 Hz, 1 H, 2-H), 3.82 (dt, *J* = 9.0, 1.7 Hz, 1 H, 4-H), 3.89 (t, *J* = 9.0 Hz, 1 H, 3-H), 4.54 (d, *J* = 3.4 Hz, 1 H, 1-H), 4.59 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.62 (d, *J* = 1.7 Hz, 1 H, 6-H), 4.62 (d, *J* = 1.7 Hz, 1 H, 6'-H), 4.67 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.83 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 7.14–7.29 (m, 15 H, arom H).

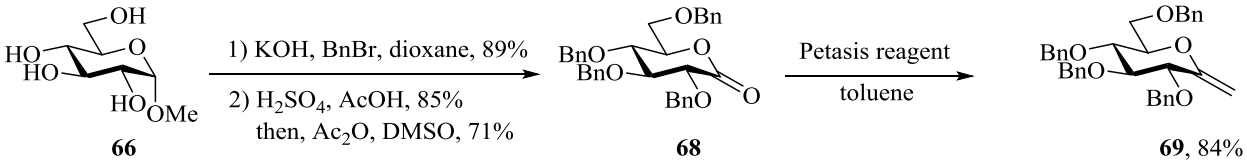
^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 55.4 (q, O*Me*), 73.5, 74.4, 75.7 (3t, C*H*$_2$-Ph), 79.3, 79.5, 81.1 (3d, C-3, C-4, C-2), 96.8 (t, C-6, *CH*$_2$), 99.0 (d, C-1), 127.5, 127.7, 127.8, 127.9, 127.9,

128.0, 128.3, 128.3, 128.4 (m, arom. *C*-H), 137.9, 138.0, 138.6 (3q, arom. *C*-CH_2O), 153.6 (t, C-5).

IR (film): 3402, 3063, 3031, 2928, 1723, 1635, 1497, 1454, 1208, 1073, 1022, 736, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{28}H_{30}NaO_5$: 469.1991; found: 469.2004.

Procedure for the synthesis of the *exo*-glycal 69.[65]



(1st Step)[65d]: To a solution of methyl α-D-glucopyranoside **66** (2.91 g, 15 mmol) in 1,4-dioxane (20 mL) was added potassium hydroxide (16.83 g, 0.3 mol, 20 equiv). To this solution, benzyl chloride (18.98 g, 150 mmol, 10 equiv) was added dropwise and it was stirred at 80 °C overnight. After completion, the reaction mixture was quenched by a slow addition of methanol and diluted with water (100 mL) and then extracted with diethyl ether (3 X 100 mL). The combined organic layers were washed with brine (25 mL), dried over sodium sulfate, concentrated and purified by silica gel column chromatography to afford methyl 2,3,4,6-tetra-*O*-benzyl-α-D-glucopyranoside (5.77 g, 89%) in pure form; Lit.[65d]: (Yield = 96%).

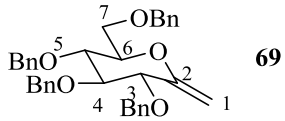
(2nd Step)[65e,f]: To a solution of methyl 2,3,4,6-tetra-*O*-benzyl-α-D-glucopyranoside (13 g, 23.43 mmol) in acetic acid (150 mL) was added 3M sulfuric acid (20 mL) and it was heated at 80 °C for 4 h. After completion, the reaction mixture was diluted with water (500 mL) and extracted with dichloromethane (3 X 100 mL). The combined organic layers were washed with saturated aqueous $NaHCO_3$ (pH = neutral), brine (100 mL), dried over sodium sulfate and concentrated to afford crude 2,3,4,6-tetra-*O*-benzyl-D-glucopyranoside (10.73 g, 85%); which was used for the next step without purification. To a solution of 2,3,4,6-tetra-*O*-benzyl-D-glucopyranoside (5 g, 9.25 mmol, 1 equiv) in dry dimethyl sulfoxide (25 mL) was added freshly distilled acetic anhydride (15 mL) under nitrogen atmosphere and it was stirred overnight. Upon completion, the reaction mixture was diluted with water (200 mL) and extracted with ethyl acetate (5 X 50 mL). The combined organic layers were washed with brine, dried over sodium sulfate, concentrated

and purified by silica gel column chromatography (petroleum ether/ethyl acetate 8:1) to afford 2,3,4,6-tetra-*O*-benzyl-D-gluconolactone **68** (3.53 g, 71%); Lit.[65f]: (Yield = 93%).

(3rd Step)[65h]: To a solution of 2,3,4,6-tetra-*O*-benzyl-D-gluconolactone **72** (1.07 g, 2 mmol) in dry toluene (1 mL) was added dimethyltitanocene (5 wt% in toluene, 16.64 mL, 4 mmol, 2 equiv) under nitrogen atmosphere and it was heated at 60 °C for 45 h in the dark. Upon completion, the solvent was removed *in vacuo* and the crude residue was purified by silica gel column chromatography (petroleum ether/MTBE 85:15) to afford *exo*-glycal **69** (0.91 g, 84%) as pale yellow solid; Lit.[65h]: (Yield = 81%).

3,4,5,7-tetra-*O*-benzyl-2,6-deoxy-D-glucohept-1-enitol (*exo-glycal*-69):

Nature = Pale yellow solid (906 mg, 84%).



69

R_f = 0.29 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +60.0 (c = 1.01 in $CHCl_3$); Lit.[65h]: $[\alpha]_D^{25}$ = +58.4 (c = 1.0 in CH_2Cl_2).

m.p. = 62–63 °C; Lit.[65h]: m.p. = 65–67 °C.

^{1}H NMR (300 MHz, $CDCl_3$): δ = 3.62 (dd, *J* = 8.0, 6.9 Hz, 1 H, 3-H), 3.64–3.74 (m, 3 H, 4-H, 5-H, 7'-H), 3.67 (dd, *J* = 11.3, 4.5 Hz, 1 H, 7-H), 3.88 (dt, *J* = 7.1, 1.2 Hz, 1 H, 6-H), 4.42 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.44 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.53 (d, *J* = 1.2 Hz, 1 H, 1-H), 4.55 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 11.2 Hz, 1 H, C*H*$_2$-Ph), 4.68 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 1.2 Hz, 1 H, 1'-H), 4.77 (d, *J* = 11.2 Hz, 1 H, C*H*$_2$-Ph), 7.04–7.26 (m, 20 H, arom H).

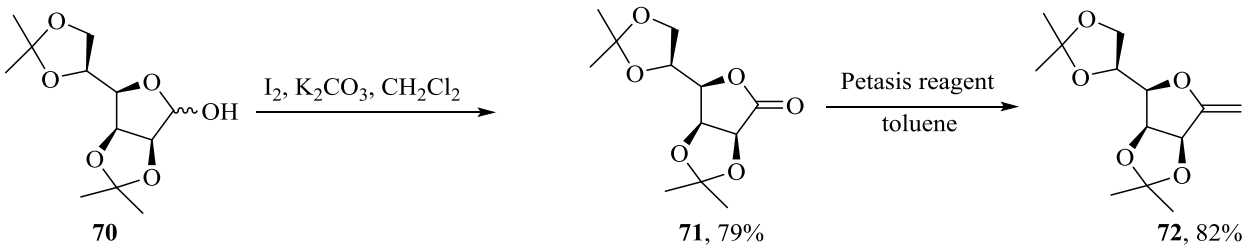
^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 68.7 (t, C-7), 72.7, 73.5, 74.3, 74.4 (4t, C*H*$_2$-Ph), 77.5, 78.5, 78.9, 84.7 (4d, C-6, C-4, C-5, C-3), 94.6 (t, C-1, *CH*$_2$), 127.6, 127.6, 127.6, 127.7, 127.8, 127.8, 127.9, 128.3, 128.3, 128.3, 128.4 (m, arom. *C*-H), 137.8, 138.0, 138.1, 138.3 (4q, arom. *C*-CH_2O), 156.3 (d, C-2).

IR (film): 3058, 3029, 2911, 2869, 1658, 1496, 1453, 1254, 1144, 1080, 905, 871, 742, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{35}H_{36}NaO_5$: 559.2460; found: 559.2410.

Anal. calcd for $C_{35}H_{36}O_5$ (536.66): C 78.33, H 6.76; found: C 77.16, H 6.76.

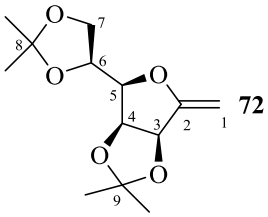
Procedure for the synthesis of the *exo*-glycal 72.[65]



(1st Step)[65g]: To a solution of 2,3:5,6-di-*O*-isopropylidine-α-D-mannofuranose **70** (1.30 g, 5 mmol) in dry dichloromethane (12 mL) was added iodine (1.90 g, 15 mmol, 3 equiv) followed by potassium carbonate (2.07 g, 15 mmol, 3 equiv), and the solution was stirred for 10 h. Upon completion, 5% Sodium thiosulfate ($Na_2S_2O_3.5H_2O$, 25 mL) was added to the dark brown colored reaction mixture and it was stirred for 5 min. The resulting colorless mixture was further diluted with water (50 mL) and extracted with dichloromethane (3 X 50 mL). The combined organic layers were washed with brine, dried over sodium sulfate, concentrated and purified by silica gel column chromatography (petroleum ether/MTBE 80:20) to afford 2,3:5,6-di-*O*-isopropylidine-α-D-mannofuranolactone **71** (1.02 g, 79%); Lit.[65g]: (Yield = 100%).

(2nd Step)[65h]: To a solution of 2,3:5,6-di-*O*-isopropylidine-*α*-D-mannofuranolactone **71** (0.77 g, 3 mmol) in dry toluene (1 mL) was added dimethyltitanocene (5 wt% in toluene, 24.96 mL, 6 mmol, 2 equiv) under argon atmosphere and it was heated at 60 °C for 24 h in the dark. Upon completion, the solvent was removed under reduced pressure and the crude residue was purified by silica gel column chromatography (petroleum ether/MTBE 90:10) to afford *exo*-glycal **72** (0.63 g, 82%) as pale yellow liquid; Lit.[65h]: (Yield = 82%).

3,4:6,7-di-*O*-isopropylidine-2,5-deoxy-D-mannohept-1-enitol (*exo-glycal*-72):



Nature = Pale yellow oil (633 mg, 82%).

R_f = 0.35 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +110.9 (c = 1.08 in $CHCl_3$); Lit.[65h]: $[\alpha]_D^{23}$ = +112.5 (c = 0.36 in $CHCl_3$).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.31, 1.31, 1.38, 1.41 (4s, 12 H, *Me*), 3.97 (dd, *J* = 7.6, 3.8 Hz, 1 H, 5-H), 4.00 (dd, *J* = 9.0, 4.9 Hz, 1 H, 7-H), 4.05 (dd, *J* = 9.0, 6.4 Hz, 1 H, 7'-H), 4.18 (dd, *J* =

1.9, 1.1 Hz, 1 H, 1-H), 4.36 (ddd, *J* = 7.6, 6.4, 4.9 Hz, 1 H, 6-H), 4.40 (dd, *J* = 1.9, 1.1 Hz, 1 H, 1'-H), 4.69 (dd, *J* = 6.0, 3.8 Hz, 1 H, 4-H), 4.99 (d, *J* = 6.0 Hz, 1 H, 3-H).

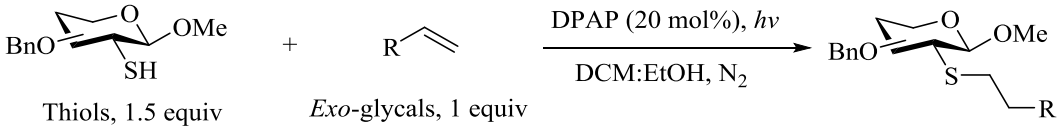
^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 25.1, 25.7, 26.7, 26.8 (4q, *Me*), 66.4 (t, C-7), 73.1, 78.4, 79.9, 82.2 (4d, C-6, C-4, C-3, C-5), 86.3 (t, C-1, *CH_2*), 109.2, 113.4 (C-8, C-9), 161.4 (d, C-2).

IR (film): 3431, 2986, 2838, 1677, 1456, 1371, 1212, 1156, 1065, 844, 705 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{13}H_{21}O_5$: 257.1389; found: 257.1381.

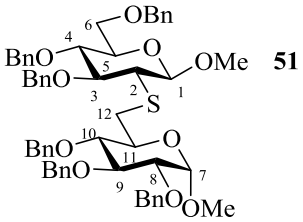
Anal. calcd for $C_{13}H_{20}O_5$ (256.29): C 60.92, H 7.87; found: C 60.77, H 8.17.

General procedure for the thiol-ene coupling between 2-thiols and *exo*-glycals.



To a solution of appropriate *exo*-glycal (0.2 mmol) in dichloromethane/ethanol (2:8, 1 mL) was added appropriate thiol (0.3 mmol, 1.5 equiv) followed by 2,2-dimethoxy-2-phenylacetophenone (DPAP, 13 mg, 20 mol %). The resulting reaction mixture was degassed under a flow of nitrogen for 10 min and irradiated under UV light until TLC showed complete conversion of starting material. The solvents were removed *in vacuo* and the crude residue was purified by silica gel column chromatography to afford the thiodisaccharides in analytically pure form.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methyl 8,9,10-tri-*O*-benzyl-12-deoxy-α-D-glucopyranosyl)-β-D-glucopyranoside (*β-gluco*-51):



51

Nature = Colorless viscous oil (175 mg, 94%).

R_f = 0.42 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +33.4 (c = 0.99 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.80 (dd, *J* = 13.5, 7.9 Hz, 1 H, 12-H, S*CH_2*), 2.84 (dd, *J* = 10.7, 8.8 Hz, 1 H, 2-H), 3.15 (dd, *J* = 13.5, 2.8 Hz, 1 H, 12'-H, S*CH_2*), 3.21 (s, 3 H, O*Me*), 3.26 (dd, *J* = 10.7, 8.8 Hz, 1 H, 3-H), 3.34 (ddd, *J* = 9.8, 4.5, 2.2 Hz, 1 H, 5-H), 3.34 (dd, *J* = 9.8, 8.7 Hz, 1 H, 9-H), 3.38 (dd, *J* = 9.8, 4.1 Hz, 1 H, 8-H), 3.40 (s, 3 H, O*Me*), 3.52 (dd, *J* = 9.8, 8.8 Hz,

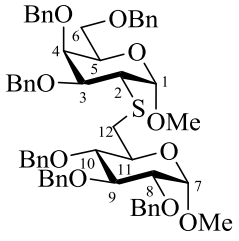
1 H, 4-H), 3.61 (dd, *J* = 10.7, 4.5 Hz, 1 H, 6-H), 3.65 (dd, *J* = 10.7, 2.2 Hz, 1 H, 6'-H), 3.74 (ddd, *J* = 9.8, 7.9, 2.8 Hz, 1 H, 11-H), 3.87 (dd, *J* = 9.8, 8.7 Hz, 1 H, 10-H), 4.13 (d, *J* = 8.8 Hz, 1 H, 1-H), 4.45 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.46 (d, *J* = 4.1 Hz, 1 H, 7-H), 4.46 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.53 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.63 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.70 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.83 (d, *J* = 10.8 Hz, 1 H, C*H*$_2$-Ph), 4.88 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 7.06–7.30 (m, 30 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 34.5 (t, C-12, S*CH*$_2$), 52.9 (d, C-2), 55.0, 56.9 (2q, O*Me*), 68.8 (t, C-6), 70.3 (d, C-11), 73.2, 73.4 (2t, C*H*$_2$-Ph), 74.7 (d, C-5), 74.8, 75.0, 75.6, 76.0 (4t, C*H*$_2$-Ph), 79.0, 80.0, 80.6, 81.8, 83.1 (5d, C-4, C-8, C-9, C-10, C-3), 97.7, 106.0 (2d, C-7, C-1), 127.5, 127.5, 127.7, 127.7, 127.8, 127.9, 128.0, 128.3, 128.3, 128.3 (m, arom. *C*-H), 138.9, 138.0, 138.1, 138.1, 138.2, 138.7 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3479, 3060, 2906, 1603, 1496, 1453, 1358, 1207, 1046, 735, 969 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{56}H_{62}NaO_{10}S$: 949.3961; found: 949.4015.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methyl 8,9,10-tri-*O*-benzyl-12-deoxy-α-D-glucopyranosyl)-α-D-galactopyranoside (*α-galacto*-73):



73

Nature = Colorless viscous oil (139 mg, 75%).

R_f = 0.31 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +24.2 (c = 1.04 in $CHCl_3$).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.58 (dd, *J* = 13.9, 6.9 Hz, 1 H, 12-H, S*CH*$_2$), 2.81 (dd, *J* = 13.9, 2.9 Hz, 1 H, 12'-H, S*CH*$_2$), 3.07 (d, *J* = 5.0 Hz, 1 H, 2-H), 3.12, 3.21 (2s, 6 H, O*Me*), 3.26 (dd, *J* = 13.1, 2.5 Hz, 1 H, 6-H), 3.40 (dd, *J* = 9.7, 3.5 Hz, 1 H, 8-H), 3.46 (dd, *J* = 9.7, 8.9 Hz, 1 H, 9-H), 3.56 (dd, *J* = 13.1, 4.9 Hz, 1 H, 6'-H), 3.69 (t, *J* = 2.3 Hz, 1 H, 4-H), 3.73 (ddd, *J* = 9.8, 6.9, 2.9 Hz, 1 H, 11-H), 3.78-3.82 (m, 1 H, 5-H), 3.89 (dd, *J* = 9.8, 8.9 Hz, 1 H, 10-H), 3.90 (dd, *J* = 5.0, 2.3 Hz, 1 H, 3-H), 4.29 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.39 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.40 (s, 1 H, 1-H), 4.46 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.59 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.60 (d, *J* = 12.0 Hz, 1 H,

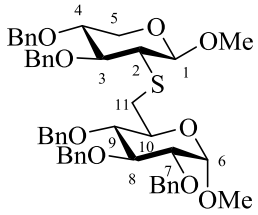
C*H*$_2$-Ph), 4.69 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 4.71–4.77 (m, 2 H, C*H*$_2$-Ph), 4.81 (d, *J* = 3.5 Hz, 1 H, 7-H), 4.85 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.93 (d, *J* = 11.5 Hz, 1 H, C*H*$_2$-Ph), 7.13–7.25 (m, 30 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 36.4 (t, C-12, S*CH*$_2$), 49.7 (d, C-2), 55.1, 55.3 (2q, O*Me*), 69.4 (t, C-6), 70.5 (d, C-4), 70.6 (t, C*H*$_2$-Ph), 71.1, 71.1 (2d, C-5, C-11), 73.4, 73.5, 73.7, 75.2, 75.7 (5t, C*H*$_2$-Ph), 75.9, 79.9, 80.3, 82.0 (4d, C-3, C-9, C-8, C-10), 98.0, 102.9 (2d, C-7, C-1), 127.3, 127.6, 127.6, 127.7, 127.9, 127.9, 128.1, 128.1, 128.2, 128.4, 128.5 (m, arom. *C*-H), 138.2, 138.2, 138.3, 138.3, 138.8, 138.9 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3029, 2921, 1701, 1496, 1453, 1205, 1051, 734, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{56}H_{63}O_{10}S$: 927.4142; found: 927.4080.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-(methyl 7,8,9-tri-*O*-benzyl-11-deoxy-α-D-glucopyranosyl)-β-D-xylopyranoside (β-*xylo*-74):



74

Nature = Colorless viscous oil (123 mg, 76%).

R_f = 0.33 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +28.8 (c = 1.01 in $CHCl_3$).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 2.73 (dd, *J* = 10.7, 8.2 Hz, 1 H, 2-H), 2.76 (dd, *J* = 13.9, 8.3 Hz, 1 H, 11-H, S*CH*$_2$), 3.10 (dd, *J* = 13.9, 2.6 Hz, 1 H, 11'-H, S*CH*$_2$), 3.11 (dd, *J* = 11.6, 9.7 Hz, 1 H, 5-H), 3.22 (s, 3 H, O*Me*), 3.23 (dd, *J* = 10.7, 8.2 Hz, 1 H, 3-H), 3.33 (t, *J* = 9.7 Hz, 1 H, 9-H), 3.35 (s, 3 H, O*Me*), 3.38 (dd, *J* = 9.7, 3.5 Hz, 1 H, 7-H), 3.50 (ddd, *J* = 9.7, 8.2, 5.0 Hz, 1 H, 4-H), 3.73 (ddd, *J* = 9.7, 8.3, 2.6 Hz, 1 H, 10-H), 3.87 (t, *J* = 9.7 Hz, 1 H, 8-H), 3.88 (dd, *J* = 11.6, 5.0 Hz, 1 H, 5'-H), 4.11 (d, *J* = 8.2 Hz, 1 H, 1-H), 4.44 (d, *J* = 3.5 Hz, 1 H, 6-H), 4.51 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.51 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.61 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.64 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.75 (s, 2 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.88 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 7.13–7.32 (m, 25 H, arom H).

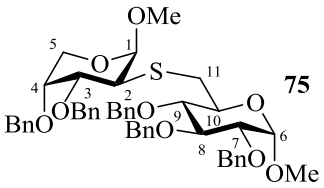
^{13}C APT NMR (125 MHz, $CDCl_3$): δ = 34.6 (t, C-11, S*CH*$_2$), 52.2 (d, C-2), 55.0, 56.8 (2q, O*Me*), 63.4 (d, C-5), 70.5 (d, C-10), 73.0, 73.2, 75.0, 75.6, 75.7 (5t, C*H*$_2$-Ph), 78.8, 80.1, 80.6, 81.8, 81.9 (5d, C-9, C-7, C-4, C-8, C-3), 97.7, 106.3 (2d, C-6, C-1), 127.8, 127.5, 127.6, 127.7, 127.8,

127.9, 128.0, 128.2, 128.3, 128.4 (m, arom. *C*-H), 138.0, 138.1, 138.1, 138.4, 138.8 (5q, arom. *C*-CH_2O).

IR (film): v = 3060, 3029, 2922, 1496, 1453, 1263, 1070, 735, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{48}H_{54}NaO_9S$: 829.3386; found: 829.3304.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-(methyl 7,8,9-tri-*O*-benzyl-11-deoxy-α-D-glucopyranosyl)-β-D-arabinopyranoside (β-*arabino*-75):



75

Nature = Colorless viscous oil (120 mg, 74%).

R_f = 0.30 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +12.6 (c = 1.02 in $CHCl_3$).

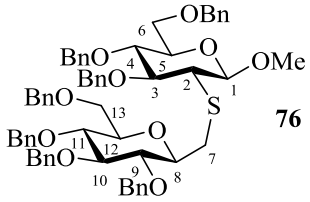
^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.66 (dd, *J* = 7.9, 2.9 Hz, 1 H, 2-H), 2.76 (dd, *J* = 13.8, 7.2 Hz, 1 H, 11-H, S*CH*$_2$), 3.00 (dd, *J* = 13.8, 2.3 Hz, 1 H, 11'-H, S*CH*$_2$), 3.27, 3.31 (2s, 6 H, O*Me*), 3.34 (dd, *J* = 9.5, 9.0 Hz, 1 H, 9-H), 3.41 (dd, *J* = 9.8, 3.8 Hz, 1 H, 7-H), 3.51 (ddd, *J* = 9.5, 7.2, 2.3 Hz, 1 H, 10-H), 3.68–3.78 (m, 3 H, 4-H, 5-H, 5'-H), 3.88 (dd, *J* = 9.8, 9.0 Hz, 1 H, 8-H), 4.01 (t, *J* = 2.9 Hz, 1 H, 3-H), 4.47 (d, *J* = 3.8 Hz, 1 H, 6-H), 4.50 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.51–4.57 (m, 2 H, C*H*$_2$-Ph), 4.54 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.60 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.68 (d, *J* = 7.9 Hz, 1 H, 1-H), 4.69 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.88 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 6.99–7.33 (m, 25 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 34.7 (t, C-11, S*CH*$_2$), 51.4 (d, C-2), 52.2, 56.8 (2q, O*Me*), 62.2 (d, C-5), 70.4 (d, C-4), 71.7, 73.4, 74.7, 75.2, 75.8 (5t, C*H*$_2$-Ph), 76.3, 78.1, 80.2, 80.4, 82.1 (5d, C-9, C-3, C-7, C-10, C-8), 97.9, 104.2 (2d, C-6, C-1), 127.5, 127.7, 127.8, 127.9, 128.0, 128.0, 128.1, 128.2, 128.4, 128.5 (m, arom. *C*-H), 138.2, 138.2, 138.2, 138.8, 138.8 (5q, arom. *C*-CH_2O).

IR (film): v = 3667, 2979, 2903, 1494, 1451, 1401, 1250, 1051, 935, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{48}H_{56}O_9S$: 808.3645; found: 808.3533.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methylene 9,10,11,13-tetra-*O*-benzyl-8-deoxy-*β*-D-glucopyranosyl)-*β*-D-glucopyranoside (*β-gluco*-76):



Nature = Colorless viscous oil (163 mg, 80%).

R_f = 0.32 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +6.2 (c = 0.98 in $CHCl_3$).

^{1}H NMR (500 MHz, CD_2Cl_2): δ = 2.78 (dd, *J* = 11.0, 8.8 Hz, 1 H, 2-H), 2.99 (dd, *J* = 13.6, 7.3 Hz, 1 H, 7-H, S*CH*$_2$), 3.16 (dd, *J* = 13.6, 2.9 Hz, 1 H, 7'-H, S*CH*$_2$), 3.29 (dd, *J* = 11.0, 8.5 Hz, 1 H, 3-H), 3.29 (ddd, *J* = 8.9, 5.0, 2.9 Hz, 1 H, 12-H), 3.33 (ddd, *J* = 9.1, 4.4, 1.9 Hz, 1 H, 5-H), 3.36 (dd, *J* = 9.8, 8.9 Hz, 1 H, 11-H), 3.42 (s, 3 H, O*Me*), 3.42 (ddd, *J* = 9.7, 7.3, 2.9 Hz, 1 H, 8-H), 3.48 (dd, *J* = 9.7, 8.8 Hz, 1 H, 9-H), 3.49 (dd, *J* = 9.8, 8.8 Hz, 1 H, 10-H), 3.55 (dd, *J* = 9.1, 8.5 Hz, 1 H, 4-H), 3.58–3.67 (m, 4 H, 6-H, 6'-H, 13-H, 13'-H), 4.17 (d, *J* = 8.8 Hz, 1 H, 1-H), 4.42 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.44 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.51 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.66 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.71 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.73 (d, *J* = 10.1 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.80 (d, *J* = 11.4 Hz, 1 H, C*H*$_2$-Ph), 4.80 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 7.09–7.31 (m, 35 H, arom H).

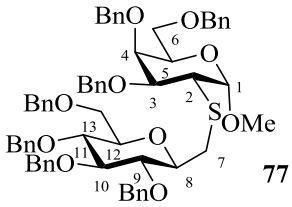
^{13}C APT NMR (125 MHz, $CDCl_3$): δ = 34.8 (t, C-7, S*CH*$_2$), 53.5 (d, C-2), 57.0 (q, O*Me*), 68.9, 68.9 (2t, C-6, C-13), 73.4, 73.5 (2t, C*H*$_2$-Ph), 74.7 (d, C-11), 74.9, 74.9, 75.4, 46.1 (4t, C*H*$_2$-Ph), 78.4, 79.1, 79.2, 79.9, 80.8, 83.3, 87.0 (7d, C-10, C-3, C-5, C-9, C-8, C-12, C-4), 105.9 (d, C-1), 127.4, 127.5, 127.5, 127.5, 127.6, 127.6, 127.7, 127.7, 127.8, 127.9, 127.9, 128.0, 128.2, 128.2, 128.3, 128.3 (m, arom. *C*-H), 138.0, 138.1, 138.1, 138.1, 138.3, 138.4, 138.6 (7q, arom. *C*-CH_2O).

IR (film): *v* = 3483, 3029, 2861, 1953, 1496, 1453, 1209, 1049, 910, 735, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{63}H_{68}NaO_{10}S$: 1039.4431; found: 1039.4409.

Anal. calcd for $C_{63}H_{68}O_{10}S$ (1017.28): C 74.38, H 6.74, S 3.15; found: C 73.57, H 6.66, S 3.44.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methylene 9,10,11,13-tetra-*O*-benzyl-8-deoxy-*β*-D-glucopyranosyl)-*α*-D-galactopyranoside (*α-galacto*-77):



77

Nature = Colorless viscous oil (184 mg, 90%).

R_f = 0.29 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = –3.4 (c = 0.84 in $CHCl_3$).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.69 (dd, *J* = 15.0, 4.9 Hz, 1 H, 7-H, S*CH*$_2$), 2.87 (dd, *J* = 15.0, 2.3 Hz, 1 H, 7'-H, S*CH*$_2$), 3.14 (dd, *J* = 10.1, 8.7 Hz, 1 H, 10-H), 3.26 (ddd, *J* = 9.7, 4.9, 2.3 Hz, 1 H, 8-H), 3.27 (s, 3 H, O*Me*), 2.44 (ddd, *J* = 9.1, 4.9, 1.9 Hz, 1 H, 12-H), 2.44 (dd, *J* = 10.5, 4.9 Hz, 1 H, 13-H), 3.51 (dd, *J* = 10.5, 1.9 Hz, 1 H, 13'-H), 3.52 (dd, *J* = 9.7, 8.7 Hz, 1 H, 9-H), 3.55–3.59 (m, 2 H, H-6, H-6'), 3.69 (d, *J* = 4.9 Hz, 1 H, 2-H), 3.71 (t, *J* = 2.3 Hz, 1 H, 4-H), 3.76 (dd, *J* = 10.1, 9.1 Hz, 1 H, 11-H), 3.86 (td, *J* = 6.4, 2.3 Hz, 1 H, 5-H), 3.96 (dd, *J* = 4.9, 2.3 Hz, 1 H, 3-H), 4.03 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.23 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.31 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.36 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.40 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.49 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.60 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.75 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.76 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 4.93 (s, 1 H, 1-H), 4.96 (d, *J* = 12.3 Hz, 1 H, C*H*$_2$-Ph), 7.00–7.31 (m, 35 H, arom H).

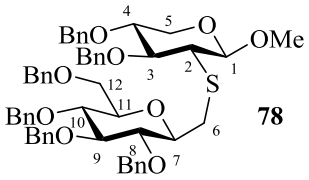
^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 33.5 (t, C-7, S*CH*$_2$), 47.3 (d, C-2), 55.0 (q, O*Me*), 69.0, 69.7 (2t, C-6, C-13), 69.8 (t, C*H*$_2$-Ph), 70.4 (d. C-5), 73.6, 73.6 (2t, C*H*$_2$-Ph), 73.9 (d, C-4), 74.1, 75.0, 75.1, 75.3 (4t, C*H*$_2$-Ph), 75.7, 78.4, 79.0, 79.3, 80.4, 87.0 (6d, C-3, C-10, C-8, C-11, C-12, C-9), 102.3 (d, C-1), 127.2, 127.3, 127.4, 127.4, 127.6, 127.7, 127.8, 127.9, 128.1, 128.1, 128.2, 128.3, 128.4, 128.4, 128.4, 128.5 (m, arom. *C*-H), 138.1, 138.2, 138.2, 138.3, 138.8, 138.9, 138.9 (7q, arom. *C*-CH_2O).

IR (film): *v* = 3060, 3029, 2906, 1952, 1603, 1496, 1453, 1357, 1090, 1052, 733, 695 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{63}H_{68}NaO_{10}S$: 1039.4431; found: 1039.4407.

Anal. calcd for $C_{63}H_{68}O_{10}S$ (1017.28): C 74.38, H 6.74, S 3.15; found: C 73.40, H 6.45, S 3.58.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-(methylene 8,9,10,12-tetra-*O*-benzyl-7-deoxy-*β*-D-glucopyranosyl)-*β*-D-xylopyranoside (*β-xylo*-78):



Nature = Colorless viscous oil (132 mg, 74%).

R_f = 0.36 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{22}$ = –10.7 (c = 1.05 in $CHCl_3$).

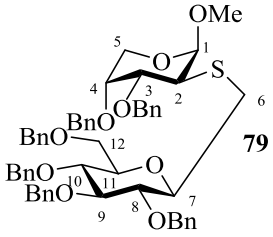
^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.76 (dd, *J* = 10.5, 8.3 Hz, 1 H, 2-H), 2.80 (dd, *J* = 13.6, 7.1 Hz, 1 H, 6-H, S*CH*$_2$), 3.15 (dd, *J* = 13.6, 2.6 Hz, 1 H, 6'-H, S*CH*$_2$), 3.12 (dd, *J* = 11.6, 9.8 Hz, 1 H, 5-H), 3.26 (dd, *J* = 10.5, 8.3 Hz, 1 H, 3-H), 3.28 (ddd, *J* = 9.3, 4.2, 1.9 Hz, 1 H, 11-H), 3.40 (dd, *J* = 9.5, 7.6 Hz, 1 H, 8-H), 3.38 (s, 3 H, O*Me*), 3.43 (ddd, *J* = 9.5, 7.1, 2.6 Hz, 1 H, 7-H), 3.45 (ddd, *J* = 9.8, 8.3, 5.0 Hz, 1 H, 4-H), 3.54 (t, *J* = 9.3 Hz, 1 H, 10-H), 3.58 (dd, *J* = 9.3, 7.6 Hz, 1 H, 9-H), 3.58 (dd, *J* = 11.2, 4.2 Hz, 1 H, 12-H), 3.63 (dd, *J* = 11.2, 1.9 Hz, 1 H, 12'-H), 3.87 (dd, *J* = 11.6, 5.0 Hz, 1 H, 5'-H), 4.14 (d, *J* = 8.3 Hz, 1 H, 1-H), 4.44 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 11.6 Hz, 2 H, C*H*$_2$-Ph), 4.51 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 12.2 Hz, 1 H, C*H*$_2$-Ph), 4.59 (d, *J* = 11.6 Hz, 1 H, C*H*$_2$-Ph), 4.69 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.2 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.2 Hz, 3 H, C*H*$_2$-Ph), 4.80 (d, *J* = 11.3 Hz, 1 H, C*H*$_2$-Ph), 7.07–7.32 (m, 30 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 34.9 (t, C-6, S*CH*$_2$), 52.8 (d, C-2), 57.0 (q, O*Me*), 63.5, 69.0 (2t, C-5, C-12), 73.1, 73.6, 75.0, 75.1, 75.5, 75.9 (6t, C*H*$_2$-Ph), 78.5, 78.9, 79.3, 80.2, 80.9, 82.1, 87.1 (7d, C-9, C-11, C-7, C-4, C-8, C-3, C-10), 106.4 (d, C-1), 127.5, 127.6, 127.7, 127.7, 127.7, 127.8, 128.0, 128.0, 128.2, 128.3, 128.4, 128.4, 128.5 (m, arom. *C*-H), 138.2, 138.2, 138.3, 138.5, 138.6, 138.7 (6q, arom. *C*-CH_2O).

IR (film): *v* = 3400, 3030, 2862, 1954, 1496, 1453, 1209, 1071, 735, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{55}H_{60}NaO_9S$: 919.3856; found: 919.3730.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-(methylene 8,9,10,12-tetra-*O*-benzyl-7-deoxy-*β*-D-glucopyranosyl)-*β*-D-arabinopyranoside (*β-arabino*-79):



Nature = Colorless viscous oil (119 mg, 66%).

R_f = 0.39 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = –19.1 (c = 1.00 in $CHCl_3$).

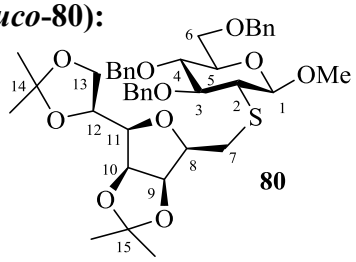
^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.71 (dd, *J* = 13.9, 8.3 Hz, 1 H, 6-H, S*CH*$_2$), 2.91 (dd, *J* = 7.9, 3.1 Hz, 1 H, 2-H), 3.03 (dd, *J* = 13.9, 2.6 Hz, 1 H, 6'-H, S*CH*$_2$), 3.31 (dd, *J* = 10.2, 8.3 Hz, 1 H, 10-H), 3.34 (s, 3 H, O*Me*), 3.36 (ddd, *J* = 9.7, 3.8, 3.1 Hz, 1 H, 4-H), 3.41 (ddd, *J* = 9.8, 8.3, 2.6 Hz, 1 H, 7-H), 3.47 (ddd, *J* = 8.3, 5.7, 2.6 Hz, 1 H, 11-H), 3.49 (dd, *J* = 10.2, 8.2 Hz, 1 H, 9-H), 3.57–3.59 (m, 2 H, H-12, H-12'), 3.60 (dd, *J* = 9.8, 8.2 Hz, 1 H, 8-H), 3.71–3.75 (m, 2 H, H-5, H-5'), 4.08 (t, *J* = 3.1 Hz, 1 H, 3-H), 4.43 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.44 (d, *J* = 12.1 Hz, 1 H, C*H*$_2$-Ph), 4.47 (d, *J* = 12.5 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.48 (d, *J* = 12.5 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.60 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.72 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.78 (d, *J* = 10.5 Hz, 1 H, C*H*$_2$-Ph), 4.79 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.81 (d, *J* = 11.1 Hz, 1 H, C*H*$_2$-Ph), 4.54 (d, *J* = 7.9 Hz, 1 H, 1-H), 7.06–7.31 (m, 30 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 34.6 (t, C-6, S*CH*$_2$), 51.5 (d, C-2), 56.9 (q, O*Me*), 62.3, 69.3 (2t, C-5, C-12), 71.6, 73.4, 74.5, 75.0, 75.3, 75.6 (6t, C*H*$_2$-Ph), 76.2, 77.8, 78.5, 79.1, 81.1, 81.5, 87.2 (7d, C-7, C-11, C-3, C-9, C-4, C-10, C-8), 104.3 (d, C-1), 127.4, 127.6, 127.7, 127.8, 128.0, 128.2, 128.5, 128.5 (m, arom. *C*-H), 138.1, 138.1, 138.3, 138.3, 138.6, 138.9 (66q, arom. *C*-CH_2O).

IR (film): *v* = 3504, 3029, 2866, 1953, 1496, 1453, 1058, 801, 696 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{55}H_{60}NaO_9S$: 919.3856; found: 919.3844.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methylene 9,10:12,13-di-*O*-isopropylidine-8,11-deoxy-D-mannofuranosyl)-*β*-D-glucopyranoside (*β-gluco*-80):



80

Nature = Colorless viscous oil (116 mg, 79%).

R_f = 0.13 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +6.4 (c = 1.22 in $CHCl_3$).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.19, 1.28, 1.35, 1.35 (4s, 12 H, *Me*), 2.68 (dd, *J* = 10.9, 8.6 Hz, 1 H, 2-H), 2.84 (dd, *J* = 13.5, 8.6 Hz, 1 H, 7-H, S*CH*$_2$), 3.01 (dd, *J* = 13.5, 5.2 Hz, 1 H, 7'-H, S*CH*$_2$), 3.25 (dd, *J* = 10.9, 8.7 Hz, 1 H, 3-H), 3.29 (dd, *J* = 7.9, 3.4 Hz, 1 H, 11-H), 3.36 (ddd, *J* = 9.8, 4.1, 2.2 Hz, 1 H, 5-H), 3.48 (s, 3 H, O*Me*), 3.54 (dd, *J* = 9.8, 8.7 Hz, 1 H, 4-H), 3.57 (ddd, *J*

= 8.6, 5.2, 3.4 Hz, 1 H, 8-H), 3.63 (dd, *J* = 11.0, 4.1 Hz, 1 H, 6-H), 3.67 (dd, *J* = 11.0, 2.2 Hz, 1 H, 6'-H), 3.93 (dd, *J* = 8.6, 4.5 Hz, 1 H, 13-H), 3.96 (dd, *J* = 8.6, 6.4 Hz, 1 H, 13'-H), 4.18 (d, *J* = 8.6 Hz, 1 H, 1-H), 4.26 (ddd, *J* = 7.9, 6.4, 4.5 Hz, 1 H, 12-H), 4.41 (dd, *J* = 6.1, 3.4 Hz, 1 H, 9-H), 4.43 (dd, *J* = 6.1, 3.4 Hz, 1 H, 10-H), 4.47 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.50 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 12.4 Hz, 1 H, C*H*$_2$-Ph), 4.73 (d, *J* = 10.9 Hz, 1 H, C*H*$_2$-Ph), 4.79 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 4.84 (d, *J* = 10.6 Hz, 1 H, C*H*$_2$-Ph), 7.08–7.32 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 24.6, 25.2, 25.6, 26.9 (4q, *Me*), 29.7 (t, C-7, S*CH*$_2$), 53.1 (d, C-2), 57.2 (q, O*Me*), 66.8, 68.7 (2t, C-13, C-6) 72.9 (d, C-12), 73.4 (t, C*H*$_2$-Ph), 74.7 (d, C-5), 74.9, 76.0 (2t, C*H*$_2$-Ph), 79.2, 80.3, 80.4, 81.3, 81.7, 82.8 (6d, C-4, C-9, C-10, C-8, C-11, C-3), 105.9 (d, C-1), 108.9, 112.2 (2s, C-14, C-15), 127.5, 127.5, 127.7, 127.7, 127.8, 128.2, 128.3 (m, arom. *C*-H), 138.9, 138.0, 138.5 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3495, 2984, 2931, 1496, 1454, 1374, 1208, 1108, 1067, 734, 698 cm^{-1}.

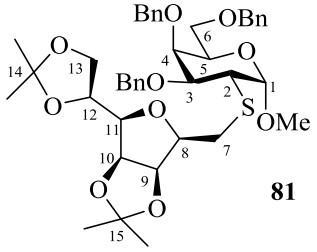
HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{41}H_{53}O_{10}S$: 737.3359; found: 737.3333.

Methyl 3,4,6-tri-*O*-benzyl-2-deoxy-2-thio-(methylene 9,10:12,13-di-*O*-isopropylidine-8,11-deoxy-D-mannofuranosyl)-α-D-galactopyranoside (*α-galacto*-81):

Nature = Colorless viscous oil (95 mg, 64%).

R_f = 0.27 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +13.3 (c = 0.50 in $CHCl_3$).



81

^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.19, 1.28, 1.35, 1.37 (4s, 12 H, *Me*), 2.72 (dd, *J* = 13.6, 7.5 Hz, 1 H, 7-H, S-*CH*$_2$), 2.78 (dd, *J* = 13.6, 6.0 Hz, 1 H, 7'-H, S*CH*$_2$), 3.26 (s, 3 H, O*Me*), 2.28 (d, *J* = 4.5 Hz, 1 H, 2-H), 3.39 (dd, *J* = 7.9, 3.4 Hz, 1 H, 11-H), 3.52 (dd, *J* = 9.8, 6.0 Hz, 1 H, 6-H), 3.55 (dd, *J* = 9.8, 6.0 Hz, 1 H, 6'-H), 3.60 (ddd, *J* = 7.5, 6.0, 3.4 Hz, 1 H, 8-H), 3.70 (t, *J* = 1.9 Hz, 1 H, 4-H), 3.81 (td, *J* = 6.0, 1.9 Hz, 1 H, 5-H), 3.94 (dd, *J* = 8.7, 4.5 Hz, 1 H, 13-H), 3.98 (dd, *J* = 8.7, 6.0 Hz, 1 H, 13'-H), 3.99 (dd, *J* = 4.5, 1.9 Hz, 1 H, 3-H), 4.29 (ddd, *J* = 7.9, 6.0, 4.5 Hz, 1 H, 12-H), 4.30 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.39 (d, *J* = 12.0 Hz, 1 H, C*H*$_2$-Ph), 4.43 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.52 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.62 (dd, *J* = 6.0, 3.4 Hz, 1 H, 9-H), 4.64

(dd, *J* = 6.0, 3.4 Hz, 1 H, 10-H), 4.70 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.88 (s, 1 H, 1-H), 4.94 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 7.12–7.34 (m, 15 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 24.6, 25.3, 25.8, 27.0 (4q, *Me*), 32.4 (t, C-7, S*CH*$_2$), 49.2 (d, C-2), 55.0 (q, O*Me*), 67.0 (t, C-13), 69.6, (t, C*H*$_2$-Ph), 70.1 (t, C-6), 70.4, 73.1, 73.4 (3d, C-12, C-4, C-5), 73.5, 73.9 (2t, C*H*$_2$-Ph), 75.6, 80.6, 80.8, 81.8, 82.7 (5d, C-3, C-10, C-9, C-11, C-8), 102.7 (d, C-1), 109.1, 112.4 (2s, C-14, C-15), 127.4, 127.4, 127.6, 127.7, 128.1, 128.4, 128.4, 128.4 (m, arom. *C*-H), 138.2, 138.4, 138.9 (3q, arom. *C*-CH_2O).

IR (film): *v* = 3500, 2988, 2929, 1952, 1496, 1454, 1375, 1210, 1158, 1053, 747, 698 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{41}H_{53}O_{10}S$: 737.3359; found: 737.3332.

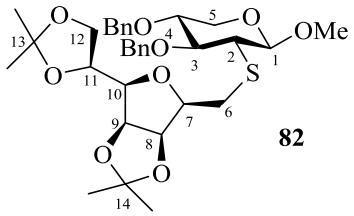
Anal. calcd for $C_{41}H_{52}O_{10}S$ (736.91): C 66.83, H 7.11, S 4.35; found: C 66.32, H 6.85, S 4.64.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-(methylene 9,10:12,13-di-*O*-isopropylidine-8,11-deoxy-D-mannofuranosyl)-*β*-D-xylopyranoside (*β*-*xylo*-82):

Nature = Colorless viscous oil (106 mg, 86%).

R_f = 0.35 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = +3.9 (c = 1.07 in $CHCl_3$).



82

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.20, 1.28, 1.35, 1.35 (4s, 12 H, *Me*), 2.57 (dd, *J* = 10.7, 8.5 Hz, 1 H, 2-H), 2.82 (dd, *J* = 13.6, 8.8 Hz, 1 H, 6-H, S*CH*$_2$), 2.97 (dd, *J* = 13.6, 5.0 Hz, 1 H, 6'-H, S-*CH*$_2$), 3.13 (dd, *J* = 11.7, 10.1 Hz, 1 H, 5-H), 3.20 (dd, *J* = 10.7, 8.5 Hz, 1 H, 3-H), 4.29 (dd, *J* = 7.9, 3.4 Hz, 1 H, 10-H), 3.43 (s, 3 H, O*Me*), 3.52 (ddd, *J* = 10.1, 8.5, 5.0 Hz, 1 H, 4-H), 3.56 (ddd, *J* = 8.8, 5.0, 3.4 Hz, 1 H, 7-H), 3.90 (dd, *J* = 11.7, 5.0 Hz, 1 H, 5'-H), 3.92 (dd, *J* = 8.5, 4.7 Hz, 1 H, 12-H), 3.96 (dd, *J* = 8.5, 6.3 Hz, 1 H, 12'-H), 4.15 (d, *J* = 8.5 Hz, 1 H, 1-H), 4.25 (ddd, *J* = 7.9, 6.3, 4.7 Hz, 1 H, 11-H), 4.39 (dd, *J* = 6.3, 3.4 Hz, 1 H, 9-H), 4.44 (dd, *J* = 6.3, 3.4 Hz, 1 H, 8-H), 4.55 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.64 (d, *J* = 11.7 Hz, 1 H, C*H*$_2$-Ph), 4.74 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 4.86 (d, *J* = 10.7 Hz, 1 H, C*H*$_2$-Ph), 7.18–7.33 (m, 10 H, arom H).

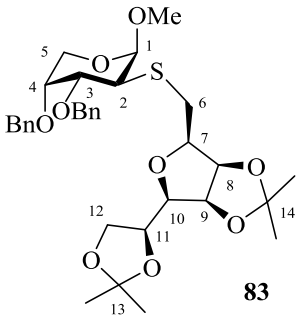
^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 24.5, 25.1, 25.6, 26.8 (4q, *Me*), 29.8 (t, C-7, S*CH*$_2$), 52.4 (d, C-2), 57.0 (q, O*Me*), 63.4, 66.7 (2t, C-12, C-5), 72.9 (d, C-11), 73.0, 75.8 (2t, C*H*$_2$-Ph), 78.8,

80.2, 80.3, 81.2, 81.6 (5d, C-4, C-8, C-9, C-7, C-10), 106.3 (d, C-1), 108.8, 112.1 (2s, C-13, C-14), 127.5, 127.6, 127.7, 127.8, 128.1, 128.4 (m, arom. *C*-H), 137.9, 138.5 (2q, arom. *C*-CH_2O).

IR (film): v = 3463, 3060, 2932, 2865, 1956, 1454, 1209, 1073, 907, 934, 699 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + Na]^+$ Calcd for $C_{33}H_{44}NaO_9S$: 639.2604; found: 639.2580.

Methyl 3,4-di-*O*-benzyl-2-deoxy-2-thio-(methylene 9,10:12,13-di-*O*-isopropylidine-8,11-deoxy-D-mannofuranosyl)-*β*-D-arabinopyranoside (*β-arabino*-83):



83

Nature = Colorless viscous oil (107 mg, 87%).

R_f = 0.30 (hexane/ethyl acetate 8:2).

$[\alpha]_D^{23}$ = –15.8 (c = 0.30 in $CHCl_3$).

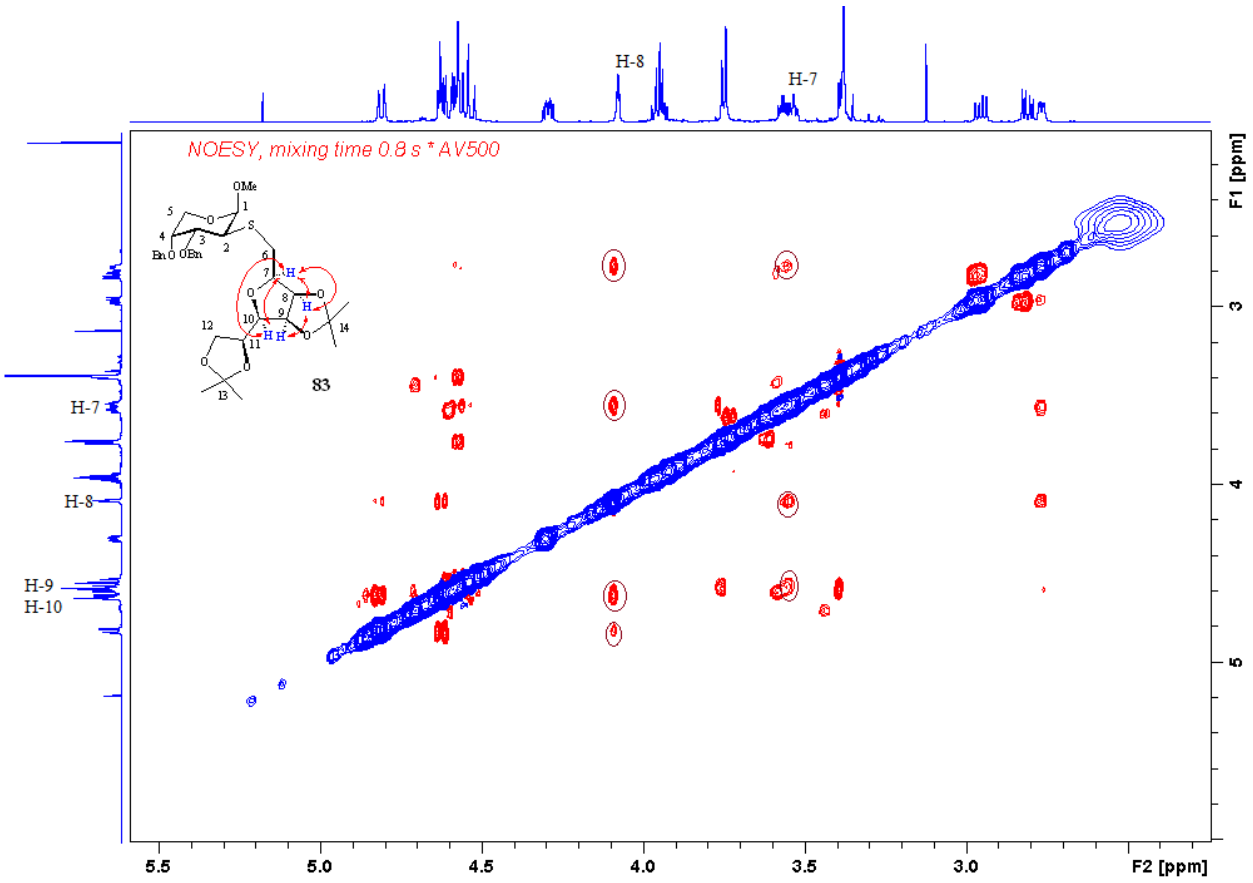
^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.24, 1.29, 1.36, 1.37 (4s, 12 H, *Me*), 2.76 (dd, *J* = 7.7, 3.4 Hz, 1 H, 2-H), 2.81 (dd, *J* = 13.9, 6.0 Hz, 1 H, 6-H, S*CH*$_2$), 2.95 (dd, *J* = 13.9, 7.5 Hz, 1 H, 6'-H, S-*CH*$_2$), 3.38 (dd, *J* = 7.5, 3.4 Hz, 1 H, 3-H), 3.38 (s, 3 H, O*Me*), 3.53 (ddd, *J* = 7.5, 6.0, 2.3 Hz, 1 H, 7-H), 3.57 (ddd, *J* = 9.7, 6.8, 2.9 Hz, 1 H, 11-H), 3.74–3.76 (m, 2 H, 12-H, 12'-H), 3.94 (dd, *J* = 8.6, 4.6 Hz, 1 H, 5-H), 3.96 (dd, *J* = 8.6, 6.0 Hz, 1 H, 5'-H), 4.08 (dd, *J* = 3.0, 2.3 Hz, 1 H, 8-H), 4.29 (ddd, *J* = 7.5, 6.0, 4.6 Hz, 1 H, 4-H), 4.53 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.55 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.56 (d, *J* = 7.7 Hz, 1 H, 1-H), 4.59 (dd, *J* = 6.0, 3.0 Hz, 1 H, 9-H), 4.62 (dd, *J* = 9.7, 6.0 Hz, 1 H, 10-H), 4.62 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 4.81 (d, *J* = 11.0 Hz, 1 H, C*H*$_2$-Ph), 7.17–7.34 (m, 10 H, arom H).

^{13}C APT NMR (75 MHz, $CDCl_3$): δ = 24.8, 25.3, 25.8, 27.1 (4q, *Me*), 30.4 (t, C-6, S*CH*$_2$), 51.1 (d, C-2), 56.9 (q, O*Me*), 62.2, 66.9 (2t, C-12, C-5), 71.6 (t, C*H*$_2$-Ph), 70.0 (d, C-4), 74.6 (t, C*H*$_2$-Ph), 76.1, 77.8, 80.6, 81.1, 81.8, 82.9 (6d, C-7, C-8, C-10, C-9, C-3, C-11), 104.2 (d, C-1), 109.1, 112.5 (2s, C-13, C-14), 127.5, 127.5, 127.8, 127.8, 128.2, 128.5 (m, arom. *C*-H), 138.1, 138.8 (2q, arom. *C*-CH_2O).

IR (film): v = 3477, 3060, 2982, 2872, 2248, 1496, 1454, 1375, 1209, 1063, 731, 700 cm^{-1}.

HRMS (ESI-TOF) *m/z* $[M + H]^+$ Calcd for $C_{33}H_{45}O_9S$: 617.2784; found: 617.2761.

NOESY spectrum (500 MHz, $CDCl_3$) of ***β-arabino*-83.**



7. References

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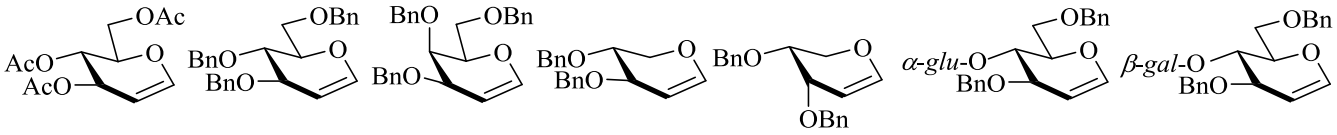
8. List of abbreviations

$(NH_4)_2S_2O_8$	Ammonium persulfate
Ac	Acetyl
AIBN	Azobisisobutyronitrile
APT	Attached proton test
Bn	Benzyl
DBU	1,8-Diazabicyclo(5.4.0)undec-7-ene
DDQ	2,3-Dichloro-5,6-dicyano-1,4-benzoquinone
DMF	Dimethylformamide
DMSO	Dimethyl sulfoxide
DPAP	2,2-Dimethoxy-2-phenylacetophenone
HMQC	Heteronuclear multiple quantum coherence
HOMO	Highest occupied molecular orbital
HRMS	High-resolution mass spectroscopy
HSQC	Heteronuclear single quantum coherence
IR	Infrared
$K_2S_2O_8$	Potassium persulfate
MTBE	Methyl *tert*-butyl ether
NH_4SCN	Ammonium thiocyanate
NMR	Nuclear magnetic resonance
NOESY	Nuclear Overhauser effect spectroscopy
rt	Room temperature
SMA	Sulfa-Michael addition
SOMO	Singly occupied molecular orbital
TBAF	Tetrabutylammonium fluoride
TBAI	Tetrabutylammonium iodide
TBAOAc	Tetrabutylammonium acetate
TEC	Thiol-ene coupling
THF	Tetrahydrofuran
TLC	Thin layer chromatography

TMS	Tetramethysilane
UV	Ultraviolet

9. Compounds index



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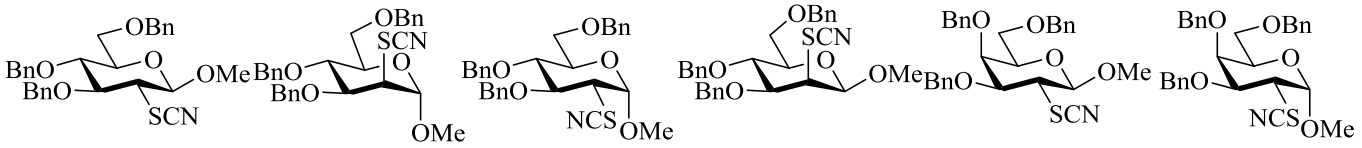

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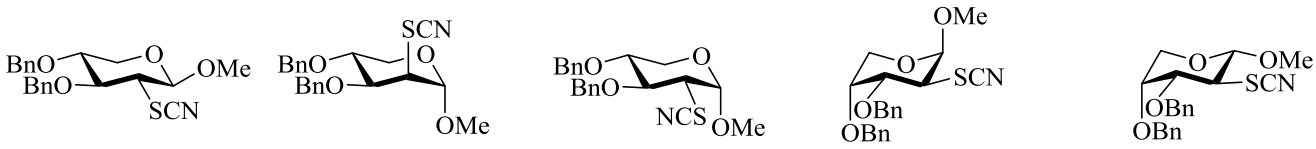
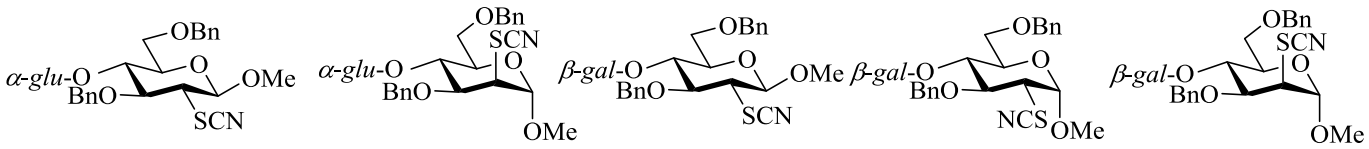
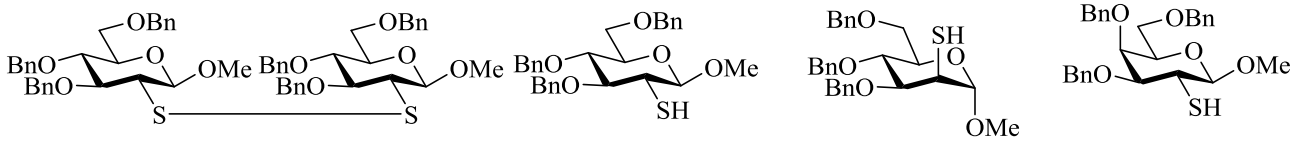


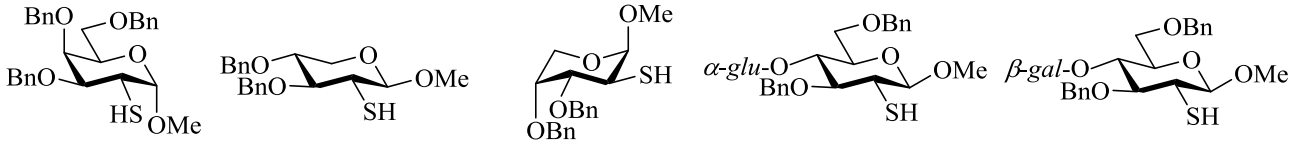
β-xylo-**6a** *α-lyxo*-**6b** *α-xylo*-**6c** *β-arabino*-**7a** α-*arabino*-**7b**



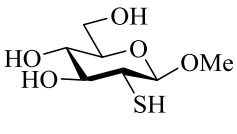
β-malto-**8a** *α-epi-malto*-**8b** *β-lacto*-**9a** *α-lacto*-**9b** *α-epi-lacto*-**9c**



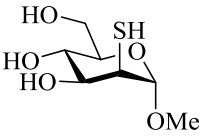
β-gluco-**15** *β-gluco*-**16** *α-manno*-**17** *β-galacto*-**18**



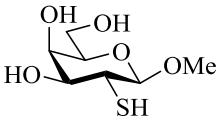
α-galacto-**19** *β-xylo*-**20** *β-arabino*-**21** *β-malto*-**22** *β-lacto*-**23**



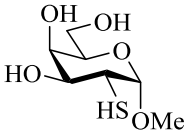
β-gluco-**24**



α-manno-**25**

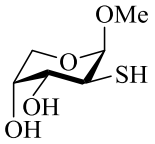


β-galacto-**26**

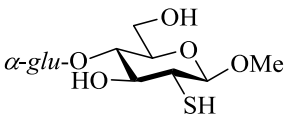


α-galacto-**27**

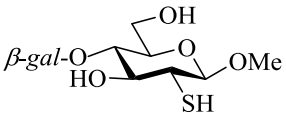
β-xylo-**28**



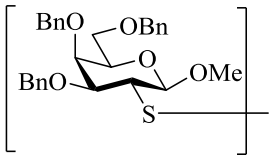
β-arabino-**29**



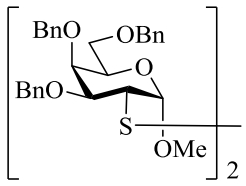
β-malto-**30**



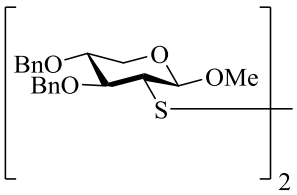
β-lacto-**31**



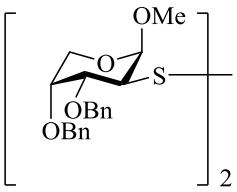
β-galacto-**32**



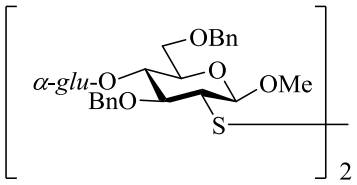
α-galacto-**33**



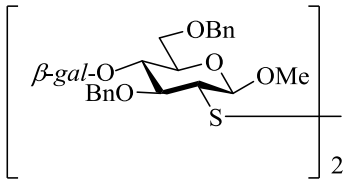
β-xylo-**34**



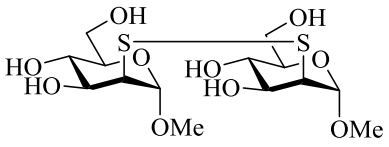
β-arabino-**35**



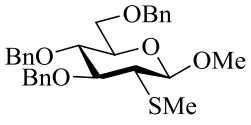
β-malto-**36**



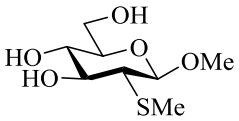
β-lacto-**37**



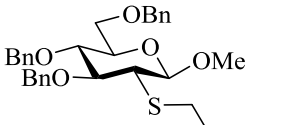
α-manno-**38**



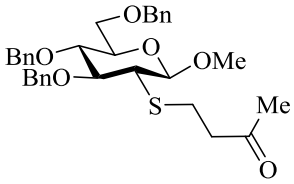
β-gluco-**39**



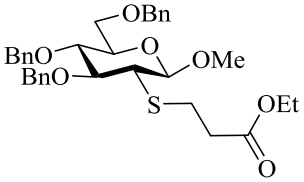
β-gluco-**40**



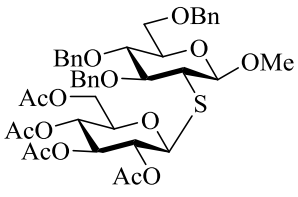
β-gluco-**42**



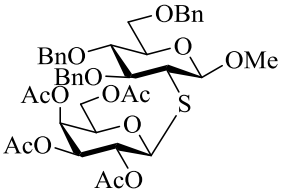
β-gluco-**43**



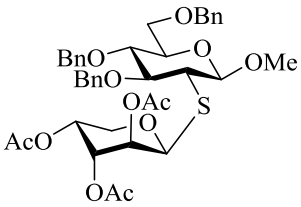
β-gluco-**44**



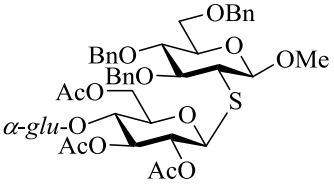
β-gluco-**46**



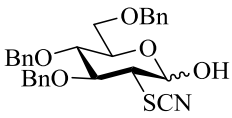
β-gluco-**47**



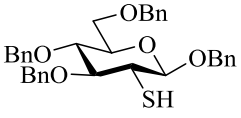
β-gluco-**48**



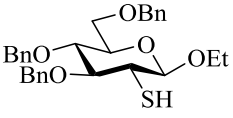
β-gluco-**49**



α/β-gluco-**52**



β-gluco-**54**



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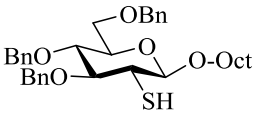
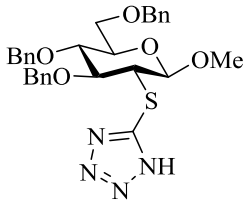
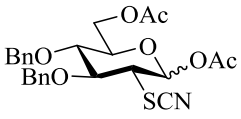


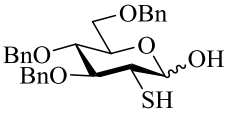
β-gluco-**56**



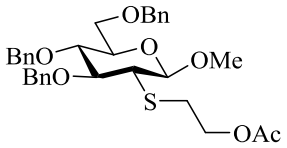
β-gluco-**59**



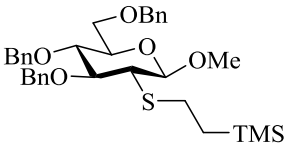
α/β-gluco-**60**



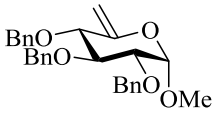
α/β-gluco-**61**



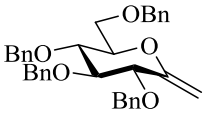
β-gluco-**64**



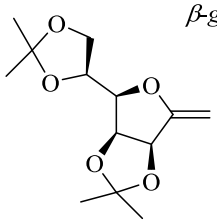
β-gluco-**65**



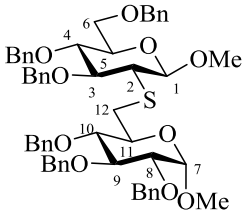
exo-glycal-**63e**



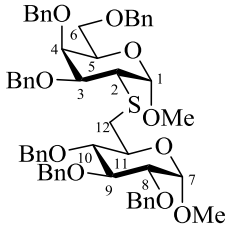
exo-glycal-**69**



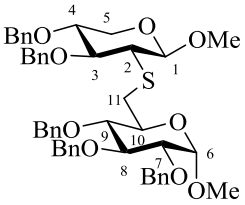
exo-glycal-**72**



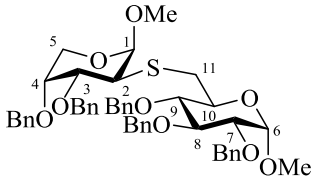
β-gluco-**51**



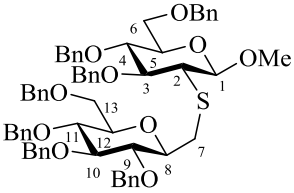
α-galacto-**73**



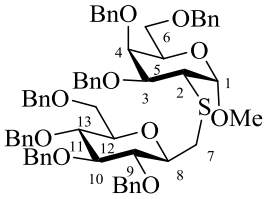
β-xylo-**74**



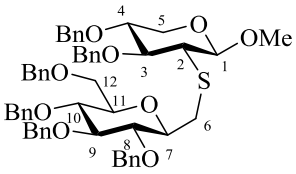
β-arabino-**75**



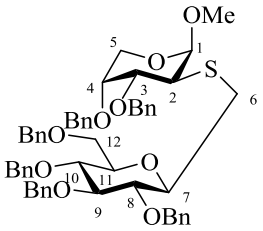
β-gluco-**76**



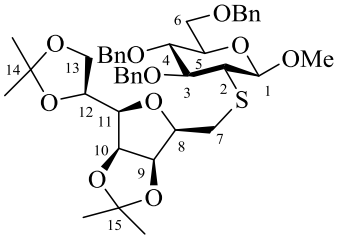
α-galacto-**77**



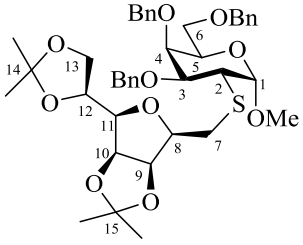
β-xylo-**78**



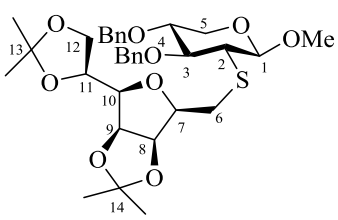
β-arabino-**79**



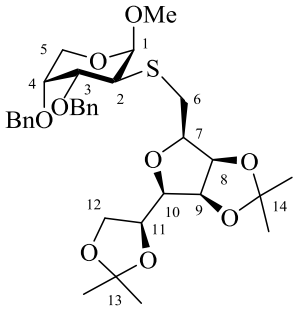
β-gluco-**80**



α-galacto-**81**



β-xylo-**82**



β-arabino-**83**

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