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Deoxythiosugar Derivatives with Furano, Pyrano, and Septano Motifs from L-Gulono-1,4-lactone and D-Glycero-D-*gulo*-heptono-1,4-lactone

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A short synthesis of thiosugar derivatives mimicking furanose, pyranose, and septanose structures has been achieved starting from L-gulono-1,4-lactone and D-glucoheptono-1,4-lactone. Different strategies used in the synthesis are: (1) a nucleophilic displacement and Michael addition; (2) epoxide ring opening and Michael addition; (3) epoxide ring opening and nucleophilic displacement process; and (4) double nucleophilic displacement. All of these reactions used benzyltriethylammonium tetrathiomolybdate, $(BnEt_3N)_2MoS_4$ as the sulfur-transfer reagent.

Introduction

There is general interest from the glycobiological perspective in the synthesis of carbohydrates and their analogs mainly as enzyme inhibitors.[1] Work in this area is synthetically challenging which elicits new insights and protocols. In particular, sulfur-containing analogs of carbohydrates are interesting from the point of view of their biological activity as glycomimetics, and are promising pharmaceutical lead compounds with potential therapeutic applications as anticancer, antiviral, and anti-AIDS agents.[2] Some representative examples, thiosugars and sulfur-containing sugar mimics, are shown in Figure 1. Research articles describing the synthesis and biological studies of thiosugars as inhibitors of glycosidases and glycosyl transferases and as scaffolds in potent HIV inhibitors are gaining more prominence.[3]

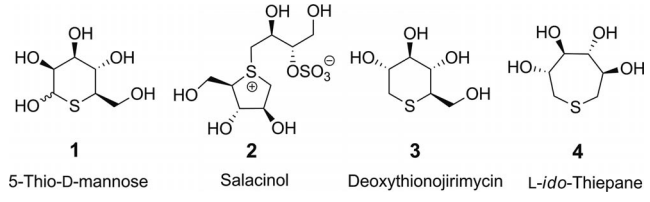

Figure 1. Thiosugars and sulfur-containing sugar mimics.

Conventional approaches for the synthesis of thiosugars include ring contraction by episulfonium ion rearrangement,[4] nucleophilic ring opening with sulfur nucleophiles,[5,4b] intramolecular cyclization of dithio or monothioacetals,[6] nucleophilic double displacement using sulfur nucleophiles,[7] and conjugate addition of sulfur nucleophiles to unsaturated esters followed by tandem cyclization.[8] However, a more general and efficient synthesis of thiosugars from carbohydrates is required in contemporary organic synthesis. After our recent success in the enantiospecific synthesis of 1-deoxy-thio-nojirimycin, 1-deoxy-thio-mannono-nojirimycin, and 1-deoxy-thio-talono-nojirimycin,[9] we became interested in the development of a general approach to the construction of various deoxythiosugars mimicking furanoses, pyranoses, and septanoses, starting from aldonolactones. In this paper, we describe a short and versatile enantiospecific synthesis of deoxythiosugars with thiofuranose, thiopyranose, and thioseptanose structures, starting from commercially available aldono-lactones, L-gulono-1,4-lactone (**5**) and D-glucoheptono-1,4-lactone (**22**).

Results and Discussion

As shown in Figure 2, different strategies were envisioned for the synthesis of thiofuranoses and thiopyranoses from dibromo lactone **6**, the synthesis of which was planned from lactone **5**.

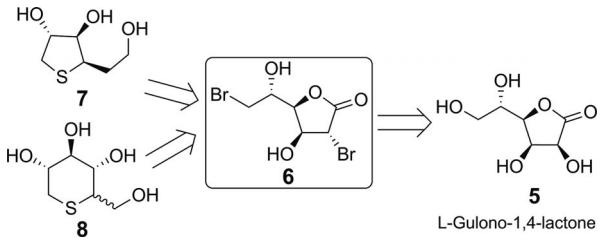

Figure 2. Retrosynthetic analysis for the synthesis of deoxythiosugars from L-gulono-1,4-lactone (**5**).

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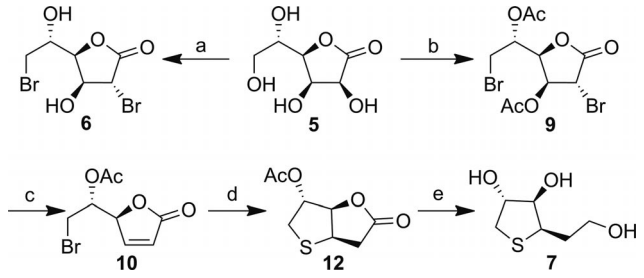
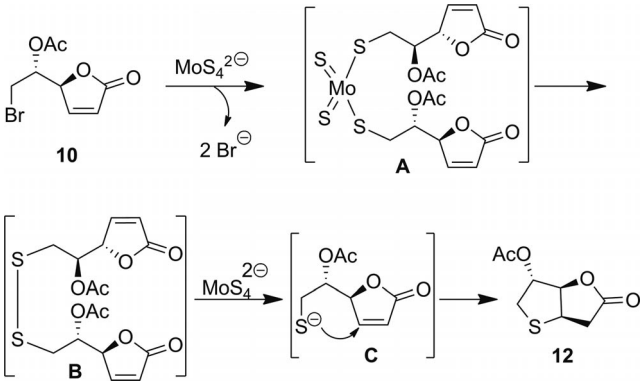
Initially, the synthesis of dibromolactone **6** was achieved by the reaction of L-gulono-1,4-lactone (**5**) with HBr/AcOH, according to the literature procedure.[10] Next, using **6** as the key intermediate, an expeditious synthesis of deoxythiosugar, 3,6-anhydro-2-deoxy-6-thio-L-*xylo*-hexitol (**7**) was envisaged. Thus, reaction of dibromolactone **6** with acetic anhydride gave acetylated product **9**[11] in 69% yield. Upon debromoacetylation using $NaHSO_3$ and Na_2SO_3, this compound yielded butenolide **10**[11], a precursor for the displacement/Michael addition reaction, in 72% yield. Sulfur-containing compound **12** was obtained in excellent yield from butenolide **10** on treatment with benzyltriethylammonium tetrathiomolybdate $(BnEt_3N)_2MoS_4$ (**11**),[12] an efficient sulfur-transfer reagent. Reduction of **12** with borohydride exchange resin (BER)[13] gave the required five-membered homothiosugar (i.e., **7**) in good yield (Scheme 1).



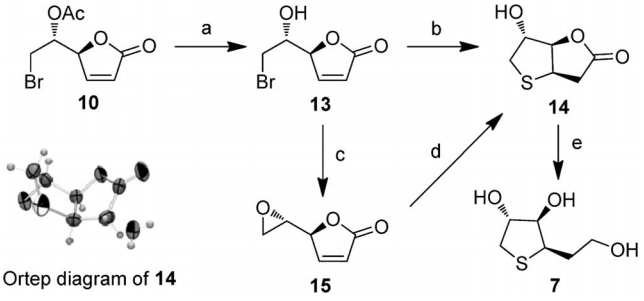
Scheme 1. Synthesis of homothiofuranose derivative **7**. *Reaction conditions:* a) HBr/AcOH, 30 °C, 4.5 h, 86%; b) HBr/AcOH, 30 °C, 3.5 h; followed by Ac_2O, 0 °C, 1 h, 69%; c) $NaHSO_3$, Na_2SO_3, MeOH/H_2O (9:1), 3 h, 72%; d) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, room temp., 1 h, 88%; e) BER, MeOH, 0 °C to r.t., 22 h, 72%.

The mechanism of formation of bicyclic lactone **12** from butenolide **10** effected by tetrathiomolybdate **11** is shown in Scheme 2. The reaction of butenolide **10** with tetrathiomolybdate **11** leads to intermediate **A** by an S_N2 displacement of the terminal bromide by the sulfide anion of **11**.[14] Intermediate **A** can then undergo an internal redox process[14] with the oxidation of the ligand and concomitant reduction of the metal center to give disulfide **B**. Based on our earlier work[12] and that of Stiefel,[15] it is anticipated that disulfide **B** undergoes reductive cleavage of the S–S bond with tetrathiomolybdate **11** to give thiolate intermediate **C**.[15] An intramolecular Michael addition of the thiolate anion to the butenolide in **C** results in the formation of bicyclic lactone **12** in a stereospecific manner.[16]



Scheme 2. Proposed mechanism for the displacement/Michael addition reaction of butenolide **10** with tetrathiomolybdate $(BnEt_3N)_2MoS_4$ (**11**).

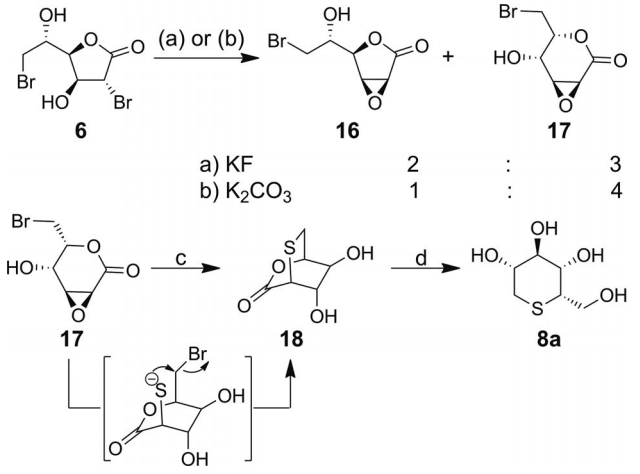
Next, **7** was obtained by an alternative route. Methanolysis of **10** using MeOH/HCl resulted in a chemoselective de-*O*-acetylation to yield butenolide **13**.[11] Reaction of **13** with benzyltriethylammonium tetrathiomolybdate (**11**) led to a smooth conversion into lactone **14** in 86% yield. The structure and configuration of **14** were unambiguously confirmed by X-ray studies. The synthesis of **7** was achieved upon reduction of **14** with BER (Scheme 3). The formation of **14** was also achieved via epoxy butenolide **15**. In this approach, butenolide **13** was treated with Ag_2O to give the required precursor (i.e., **15**).[11] As expected, treatment of **15** with $(BnEt_3N)_2MoS_4$ (**11**) resulted in a regioselective ring opening of the epoxide, followed by an intramolecular Michael reaction of the resulting thiolate to again give **14** in excellent yield. Compound **14** can be reduced to homothiofuranose derivative **7** on treatment with borohydride exchange resin (BER), as shown in Scheme 3.



Scheme 3. Synthesis of homothiofuranose derivative **7**. *Reaction conditions:* a) Methanolic HCl, 48 h, 96%; b) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, room temp., 1 h, 86%; c) Ag_2O, H_2O, 0 °C, 4 h, 70%; d) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN/EtOH, room temp., 1 h, 90%; e) BER, MeOH, 0 °C to r.t., 22 h, 73%.

After successfully achieving the synthesis of **7** by epoxide ring opening followed by Michael addition, we wanted to carry out the synthesis of a thio analog **8a** of deoxyidonojirimycin by an epoxide-ring-opening/bromide-displacement process (Scheme 4).

Reaction of dibromolactone **6** with potassium fluoride[17] gave a mixture of three products, including five-membered ring lactone epoxide **16**, six-membered ring lactone epoxide **17**, and an unidentified product (Scheme 4). The ratio of **16**/**17** was found to be ca. 2:3, based on NMR analysis. To improve the selectivity towards the formation of lactone **17**, dibromo lactone **6** was treated with K_2CO_3, which resulted in the formation of six-membered ring lactone epoxide **17** as the major product, along with a minor amount of five-membered ring lactone epoxide **16** in a ca. 4:1 ratio. The subsequent reaction of **17** with tetrathiomolybdate **11** yielded bicyclic lactone **18** in good yield. The structure and configuration of bicyclic lactone **18** were unambiguously confirmed by single-crystal X-ray analysis (Figure 3). The formation of bicyclic lactone **18** is expected to occur by initial ring-opening of the epoxide in **17** with tetrathiomolyb-



Scheme 4. Synthesis of thio-deoxy-*ido*-nojirimycin **8a** by epoxide-ring-opening/bromide-displacement process. *Reaction conditions:* a) KF, acetone, room temp., 7 h, 71% (combined yield of **16** and **17**); b) K_2CO_3, acetone, room temp., 5 h, 64% (combined yield of **16** and **17**); c) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN/EtOH, room temp., 4 h, 66%; d) BER, MeOH, 0 °C → r.t., 20 h, 67%.

date **11**, followed by displacement of the primary bromide by the thiolate nucleophile (Scheme 4).[18] Next, the synthesis of thiosugar **8a**, a thio analog of deoxy-*ido*-nojirimycin, was achieved in 67% yield from bicyclic lactone **18** by reduction with BER (Scheme 4). There are not many papers published that describe the synthesis of thio-deoxy-*ido*-nojirimycin **8a**.

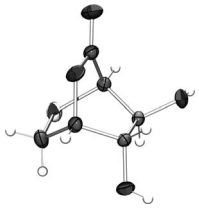
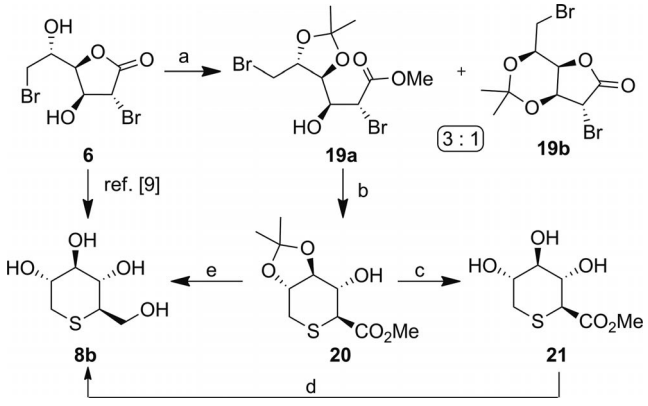


Figure 3. ORTEP diagram of bicyclic lactone **18**.

Subsequently, double displacement of dibromide **19a** with tetrathiomolybdate **11** was adopted as a strategy for the synthesis of thio-deoxy-nojirimycin **8b** (Scheme 5).

Simultaneous protection and lactone ring opening of **6** were envisaged for the synthesis of **19a**. Reaction of **6** with 2,2-dimethoxypropane (2,2-DMP) and *p*TsOH gave a mixture of **19a** and **19b** in a 3:1 ratio, with the required compound (i.e., **19a**) as the major product. The double-displacement reaction of **19a** with **11** smoothly gave acetonide-protected deoxythiosugar carboxylate **20** in 84% yield. Deprotection of the acetonide in **20** with acetic acid gave thiosugar **21** in excellent yield. X-ray analysis of deoxythiosugar carboxylate **21** unambiguously proved its structure and configuration (Figure 4). BER reduction of the ester in deoxythiosugar **21** led to thio-deoxy-nojirimycin **8b** in 86% yield (Scheme 5).

The successful synthesis of various thiosugar derivatives **12**, **14**, and **18**, ester **20** and deoxythiosugars homothiofuranose **7**, thio analog **8a** of deoxy-*ido*-nojirimycin, and thio-deoxy-nojirimycin **8b** from a single precursor **6** encouraged



Scheme 5. Synthesis of thio-deoxy-nojirimycin **8b** by double displacement process. *Reaction conditions:* a) 2,2-DMP, *p*TsOH, CH_2Cl_2, room temp., 45 min, 62%; b) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, room temp., 1 h, 84%; c) Glacial AcOH, overnight, 98%; d) BER, MeOH, 0 °C → r.t., 5 h, 86%; e) BER, MeOH, 0 °C to r.t., 10 h; followed by glacial AcOH, 78%.

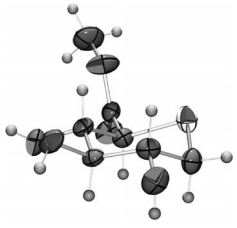


Figure 4. ORTEP diagram of thiosugar carboxylate **21**.

us to further expand the scope of this methodology by using a higher homologue. The next higher homologue chosen for the study was dibromoheptonolactone **23**, and an expeditious synthesis of thio-homo-deoxy-*gulo*-nojirimycin **27** was envisaged with **23** as a key intermediate.

The synthesis of dibromoheptonolactone **23** could be easily achieved from commercially available D-glucoheptono-1,4-lactone (**22**) by reaction with HBr/AcOH.[19] Acetylation of dibromoheptonolactone **23** using acetic anhydride gave acetylated lactone **24**. A regioselective reductive *trans*-*β*-bromo-acetoxy elimination of acetate **24** using $Na_2S_2O_5$ and Na_2SO_3 provided the required precursor, 5,6-di-*O*-acetyl-7-bromo-2,3,7-trideoxy-D-*arabino*-hept-2-enono-1,4-lactone (**25**) in 81% yield.[20] The reaction of **25** with benzyltriethylammonium tetrathiomolybdate (**11**) in CH_3CN (r.t., 5 h) resulted in thia-Michael addition in an intramolecular fashion to give 1,6-dideoxy-2,3-diacetoxy-5-thio-L-homogulono-4,7-lactone (**26**) as a white crystalline solid in 50% yield.

X-ray diffraction analysis of **26** further confirmed the structure and the configuration of this bicyclic lactone (Figure 5). The reduction of lactone **26** with borohydride exchange resin (BER) in methanol gave the six-membered ring structure, thio-homo-deoxy-*gulo*-nojirimycin **27**, in 57% yield (Scheme 6). To the best of our knowledge, this constitutes the first synthesis of thio-homo-deoxy-*gulo*-nojirimycin **27**.

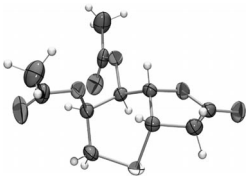
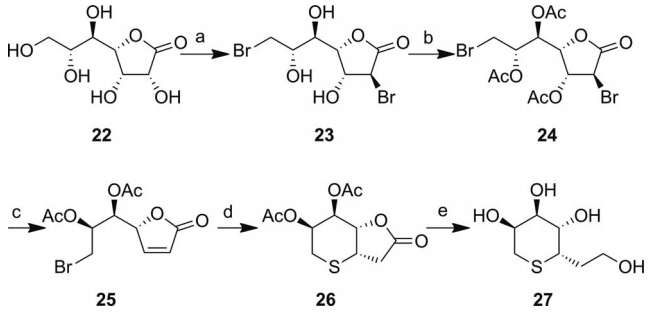


Figure 5. ORTEP diagram of 1,6-dideoxy-2,3-diacetoxy-5-thio-L-homogulono-4,7-lactone (**26**).

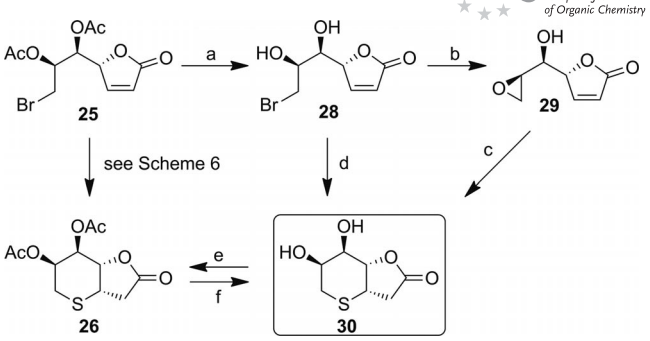


Scheme 6. Synthesis of thio-homo-deoxy-*gulo*-nojirimycin **27** by Michael addition to **25**. *Reaction conditions:* a) HBr/AcOH, 1 h; b) Ac_2O, $HClO_4$, 1 h, 51% yield over two steps; c) $Na_2S_2O_5$, Na_2SO_3, MeOH/H_2O (9:1), room temp., 3.5 h, 81%; d) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, room temp., 5 h, 50%; e) BER, MeOH, 0 °C to r.t., 17 h, 57%.

Alternatively, the synthesis of 1,6-dideoxy-2,3-diacetoxy-5-thio-L-homogulono-4,7-lactone (**26**) was also achieved by epoxide ring opening with concomitant intramolecular thia-Michael addition. Initially, olefin **25** was deacetylated using MeOH/HCl to give 7-bromo-2,3,7-trideoxy-D-*arabino*-hept-2-enono-1,4-lactone (**28**) in quantitative yield. Then reaction of olefin **28** with Ag_2O gave epoxide **29** in 82% yield. The reaction of epoxide **29** with tetrathiomolybdate **11** gave bicyclic lactone **30** in 77% yield. Acetylation of **30** gave the required sulfur compound **26** in 94% yield. The reaction of olefin **28** with tetrathiomolybdate **11** also gave compound **30** in 90% yield by a bromide-displacement reaction with concomitant thia-Michael addition. Upon deacetylation using LiOH, lactone **26** also gave **30** in 96% yield (Scheme 7).

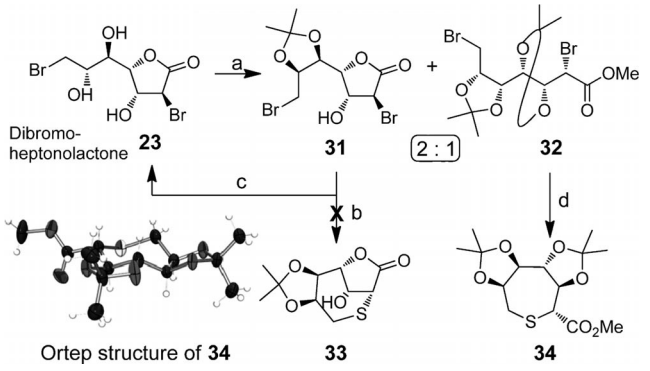
The successful synthesis of six-membered ring thiosugars from the five-membered ring lactone, D-glucoheptono-1,4-lactone (**22**),further encouraged us to synthesize a thiosugar derivative with a septanose-mimicking structure.

Accordingly, dibromoheptonolactone **23** was suitably protected using 2,2-DMP and a catalytic amount of *p*TsOH in dichloromethane to give a 2:1 mixture of isopropylidene lactone **31** and ester **32**. Unfortunately, various attempts to improve the selectivity in the acetonation reaction were unsuccessful. The reaction of major isomer, lactone **31**, with tetrathiomolybdate **11** did not yield the expected product (i.e., **33**). Acetonide **31** was then converted back into the starting dibromide (i.e., **23**) by simply stirring it in glacial acetic acid. Next, the reaction of dibromide **32** with tetrathiomolybdate **11** provided the expected seven-membered-ring-containing thioseptanose derivative, 1-deoxy-D-*glycero*-



Scheme 7. Synthesis of 1,6-dideoxy-2,3-diacetoxy-5-thio-L-homogulono-4,7-lactone (**26**). *Reaction conditions:* a) MeOH/HCl, 72 h, room temp., quantitative yield; b) Ag_2O, toluene, 80 °C, 1 h, 82%; c) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN/EtOH, room temp., 1 h, 77%; d) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, room temp., 30 min, 90%; e) Ac_2O, cat. DMAP, pyridine, 0 °C → r.t., 2 h, 94%; f) LiOH·H_2O, aq. THF, 20 min, 96%.

D-*galacto*-[(2,3)-(4,5)]-bis-isopropylidene-6-thio-6-methyl carboxylate (**34**) in 80% yield. The structure and configuration of thioseptanose derivative **34** were unambiguously confirmed by X-ray crystallography (Scheme 8).

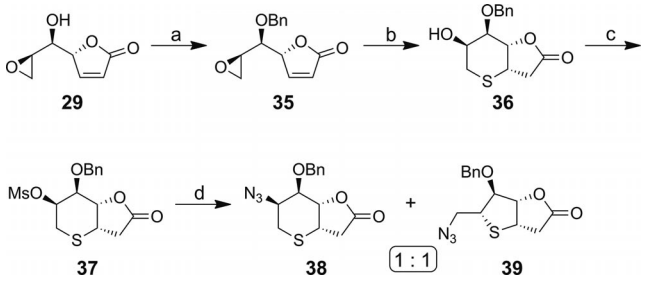


Scheme 8. Acetonation of 2,7-dibromo-2,7-dideoxy-D-*glycero*-D-*ido*-heptono-1,4-lactone (**23**). *Reaction conditions:* a) 2,2-DMP, *p*TsOH, DCM, 45 min; b) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, r.t.; c) Glacial AcOH, room temp., 8 h, 96%; d) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN, room temp., 5 h, 80%.

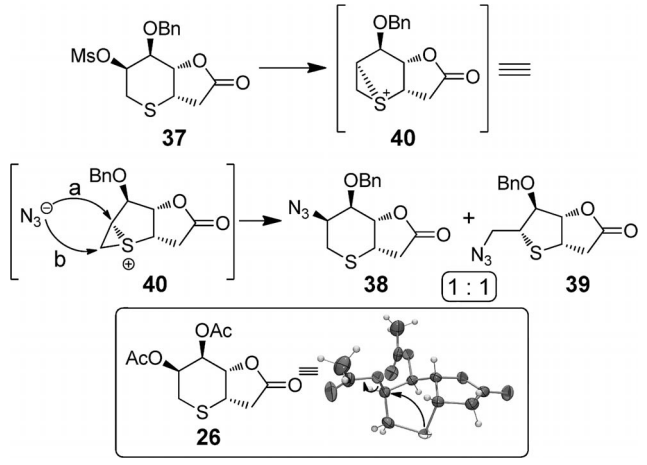
The utility of thiosugar derivatives was then extended to the synthesis of azido-thiosugar derivatives. The synthesis was started with epoxy butenolide **29** by protecting the hydroxy group as its benzyl ether. Reaction of epoxide **35** with tetrathiomolybdate **11** yielded sulfur-containing compound **36** in 80% yield. Reaction of compound **36** with mesyl chloride/pyridine provided mesylate **37**. Mesylate **37** was treated with sodium azide at 80 °C, and this produced two products in a 1:1 ratio. The products were identified as azido thiopyranose **38** and thiofuranose **39** derivatives (Scheme 9).

An explanation for the formation of azido lactones **38** and **39** can be offered based on the crystal structure of lactone **26**, since mesylate **37** has the same stereochemistry as compound **26** (Scheme 10).

Sulfur initially displaces the mesyl group in **37** due to the *anti*-periplanar arrangement of the sulfur atom and the me-



Scheme 9. Synthesis of azido sugars **38** and **39**. *Reaction conditions:* a) Ag_2O, BnBr, toluene, 80 °C, 3.5 h, 59%; b) $(BnEt_3N)_2MoS_4$ (**11**), CH_3CN/EtOH (1:1), room temp., 5 h, 80%; c) MsCl, pyridine, 0 °C to room temp. 3 h, 72%; d) NaN_3, DMF, 80 °C, 2 h, 51%.



Scheme 10. Plausible mechanism for the formation of azido thiosugar lactones **38** and **39** via episulfonium ion **40**.

syl group, to give episulfonium ion **40**. Episulfonium ion **40** can then be attacked by the azide anion in two possible ways. The azide anion can attack intermediate **40** by following path *a* to give the azido sugar **38**, or by following path *b* to give azido sugar **39**. Since the two azides (i.e., **38** and **39**) are formed in a 1:1 ratio, as observed from their NMR spectrum and by isolation, it is assumed that the attack of the azide anion by path *a* or path *b* is equally facile (Scheme 10).

Conclusions

In conclusion, the synthesis of deoxythiosugars containing five- or six-membered rings was achieved from commercially available L-gulono-1,4-lactone (**5**). Strategies used for the introduction of sulfur using benzyltriethylammonium tetrathiomolybdate (**11**) include: (1) a nucleophilic displacement and Michael addition; (2) epoxide ring opening followed by Michael addition; (3) epoxide ring opening and nucleophilic displacement process; and (4) double nucleophilic displacement. The short and efficient synthesis of thiosugars, such as thio-deoxy-*ido*-nojirimycin **8a** and thio-deoxy-nojirimycin **8b**, from a single precursor was achieved. Similarly, bromide-displacement/Michael addition, epoxide-ring-opening/Michael-addition, and double-displacement processes were used effectively for the synthesis of thiosugar derivatives **26**, **27**, **30**, and **34** from commercially available D-glucoheptono-1,4-lactone (**22**). These compounds serve as excellent precursors for the synthesis of deoxythiosugars mimicking furanose, pyranose, and septanose structures. The synthesis of azido thiopyranose derivative **38** and the ring contracted azido thiofuranose derivative **39** by episulfonium ion rearrangement is interesting, as thse compounds can serve as precursors for the synthesis of thiosugar amino acids. The methodology uses short synthetic sequences to synthesise well-known and new thiosugars and their derivatives.

Experimental Section

General Remarks: Melting points were recorded with a Büchi B540 melting point apparatus. ^1H and ^{13}C NMR spectra were recorded at 400, 300 and 100, 75 MHz, respectively, with a Bruker spectrometer. Chemical shifts are reported in parts per million downfield from the internal reference, tetramethylsilane. Coupling constants are reported wherever necessary in Hertz (Hz). Column chromatography was performed on silica gel (230–400 mesh). Mass spectra were recorded with a Q-TOF electrospray instrument. Microanalyses were recorded with a Thermo Finnigan FLASH EA 1112 CHNS analyzer. Optical rotations were recorded with a polarimeter, model P1020 (A077860638). X-ray data was recorded with a Bruker SMART APEX CCD single crystal diffractometer.

2,6-Dibromo-2,6-dideoxy-L-idono-1,4-lactone (6):[10] A solution of L-gulono-1,4-lactone (**5**; 10 g, 0.056 mol) in HBr (33% in glacial acetic acid; 56.2 mL) was stirred for 4.5 h at 30 °C. After completion of reaction, methanol (150 mL) was added slowly, and the mixture was left overnight at room temperature. The reaction mixture was then concentrated to a quarter of its volume. The concentrate was then diluted with water (200 mL), and then extracted with diethyl ether (4 × 100 mL). The organic phase was dried with $MgSO_4$ and concentrated in vacuo to yield 2,6-dibromo-2,6-dideoxy-L-idono-1,4-lactone (**6**; 14.8 g, 86%) as a pale yellow syrup. The crude product was sufficiently pure for further transformation. IR (neat): $\tilde{\nu}$ = 3443, 1779, 1428, 1221, 1183, 1100, 1059, 1014 cm^{-1}. ^1H NMR (400 MHz, [D_6]acetone): δ = 3.56 (d, J = 6.4 Hz, 2 H), 4.31 (td, J = 9.5, 5.5 Hz, 1 H), 4.63 (d, J = 5.0 Hz, 1 H), 4.83–4.75 (m, 4 H) ppm. ^{13}C NMR (100 MHz, [D_6]acetone): δ = 34.1, 44.8, 68.9, 75.5, 82.0, 171.4 ppm. HRMS: calcd. for $C_6H_8{}^{79}Br_2O_4Na$ $[M + Na]^+$ 324.8687; found 324.8684.

3,5-Di-*O*-acetyl-2,6-dibromo-2,6-dideoxy-L-idono-1,4-lactone (9):[11] L-Gulono-1,4-lactone (**5**; 10 g, 0.056 mol), was added, with stirring, to HBr (33% in glacial acetic acid; 56.6 mL, 0.6 mol), and stirred at 30 °C for 3.5 h. Then the reaction mixture was cooled to 0 °C, and acetic anhydride (21.8 mL) was added dropwise. After stirring for an additional 1 h, the mixture was slowly poured into vigorously stirred ice-water (250 mL). The resulting precipitate was filtered and then washed with water (5 × 20 mL), propan-2-ol (5 × 5 mL), and diisopropyl ether (3 × 5 mL). The residue was pure acetate **9** (15.0 g, 69%). IR (neat): $\tilde{\nu}$ = 1782, 1780, 1750, 1222, 1111, 1040, 826 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.16 (s, 6 H, -OCOCH_3), 3.41 (dd, J = 11, 4.9 Hz, 1 H, -CH_2Br), 3.42 (dd, J = 11, 6.0 Hz, 1 H, -CH_2Br), 4.46 [d, J = 5.4 Hz, 1 H, -C*H*(Br)-], 5.23–5.25 [m, 1 H, -C*H*OCO- and -C*H*(OCOCH$_3$)-], 5.56 [t, J = 5.6 Hz, 1 H, -C*H*(OCOCH$_3$)-] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.4 (-OCO*C*H$_3$), 20.9 (-OCO*C*H$_3$), 27.9 (-CH_2Br), 39.0 [-*C*H(Br)-

], 69.0 (-*C*HOCO-), 75.8 [-*C*H(OCOCH$_3$)-], 77.9 [-*C*H(OCOCH$_3$)-], 168.6 [-OC(O)-], 169.0 [-OC(O)-], 169.6 [-OC(O)-] ppm.

5-*O*-Acetyl-6-bromo-2,3,6-trideoxy-L-*threo*-hex-2-enono-1,4-lactone (10):[11] $NaHSO_3$ (2.68 g, 0.026 mol) was added to compound **9** (10 g, 0.025 mol) in methanol/water (9:1, 93 mL), and then Na_2SO_4 (6.5 g, 0.052 mol) was added to the mixture portionwise. The reaction mixture was stirred for 3 h, and then it was quenched with HCl (1 M; 78 mL), and extracted with dichloromethane (75 mL). The combined extracts were then washed with water (100 mL), dried ($MgSO_4$), and concentrated in vacuo to give compound **10** (4.62 g, 72%) as an oil. The product was pure, and was used as such in further reactions. IR (neat): $\tilde{\nu}$ = 1783, 1750, 1374, 1222, 1161, 1040, 826 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.1 (s, 3 H, -OCOCH$_3$), 3.57 (dd, J = 10.6, 6.6 Hz, 1 H, -CH$_2$Br), 3.68 (dd, J = 10.7, 6.8 Hz, 1 H, -CH$_2$Br), 5.33 (ddd, J = 6.7, 4.2, 2.5 Hz, 1 H, -CHOCO-), 5.59 [t, J = 2.2 Hz, 1 H, -C*H*(OCOCH$_3$)-], 6.21 (dd, J = 5.7, 2.0 Hz, 1 H, -CH=C*H*COO-), 7.46 (dd, J = 5.7, 1.6 Hz, 1 H, -C*H*=CHCOO-) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.3 (-OCO*C*H$_3$), 28.8 (-CH$_2$Br), 70.3 (-*C*HOCO-), 81.2 [-*C*H(OCOCH$_3$)-], 122.8 (-CH=*C*HCOO-), 152.1 (-*C*H=CHCOO-), 169.6 [-OC(O)-], 171.9 [-OC(O)-] ppm.

Synthesis of Compound 12: $(BnEt_3N)_2MoS_4$[12] (3.75 g, 6 mmol) was added to a solution of bromobutenolide **10** (0.7 g, 3 mmol) in acetonitrile (25 mL), and the reaction mixture was stirred for 1 h. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The organic phase was then concentrated to give the crude product, which, upon column chromatography on silica gel (elution with hexanes/ethyl acetate, 2:3), gave a white solid. This was recrystallized from $CHCl_3$ to give bicyclic lactone **12** (0.5 g, 88%) as colorless blocks; m.p. 113–114 °C. $[\alpha]_D$ = +132.0 (c = 1.0, $CHCl_3$). IR (neat): $\tilde{\nu}$ = 1789, 1750, 1376, 1250, 1168, 1136, 1047, 980 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.12 (s, 3 H, -OCOCH$_3$); 2.78 (d, J = 18.1 Hz, 1 H, -CH$_2$COO-), 3.01 (dd, J = 18.7, 7.3 Hz, 2 H, -CH$_2$COO- and -SCH$_2$-), 3.40 (dd, J = 12.7, 3.9 Hz, 1 H, -SCH$_2$-), 4.21 (t, J = 6.4 Hz, 1 H, -SCH-), 4.96 (d, J = 4.8 Hz, 1 H, -CHOCO-), 5.63 [s, 1 H, -C*H*(OCOCH$_3$)-] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.9 (-OCO*C*H$_3$), 36.1 (-*C*H$_2$COO-), 37.8 (-SCH$_2$-), 44.7 (-SCH-), 78.4 (-*C*HOCO-), 87.1 [-*C*H(OCOCH$_3$)-], 169.6 [-OC(O)-], 174.1 [-OC(O)-] ppm. HRMS: calcd. for $C_8H_{10}O_4SNa$ [M + Na]$^+$ 225.0198; found 225.0193.

Preparation of Borohydride Exchange Resin (BER):[13] A solution of sodium borohydride (0.5 M, 100 mL) in water was stirred with Amberlite IRA-400 Cl$^-$ resin (10.0 g) for 1 h. The borohydride-bound ion exchange resin was washed thoroughly with distilled water and dried in vacuo at 60° C for 5 h.

BER Reduction of Compound 12 to Homothiofuranose Derivative 7: BER (4.0 g, 0.012 mol) was added to a stirred solution of lactone **12** (0.3 g, 1.48 mmol) in dry methanol (18 mL) at 0 °C, and the solution was stirred for 22 h. The reaction mixture was filtered, methanol (10 mL) was added to the resin, and the methanol/resin mixture was sonicated (ultrasonic cleaning bath, 20 kHz) for 5 min at room temperature. The reaction mixture was then neutralized with glacial acetic acid. The mixture was filtered, and the filtrate was concentrated in vacuo to give the crude product. This residue was then subjected to column chromatography on silica gel (eluting with methanol/chloroform, 1.5:8.5) to give homothiosugar **7** (0.175 g, 72%) as a gummy solid. $[\alpha]_D$ = +48.0 (c = 1.0, MeOH). IR (neat): $\tilde{\nu}$ = 3404, 3394, 3384, 1671, 1523, 1252, 1102, 1022, 1070, 850 cm^{-1}. ^{1}H NMR (400 MHz, CD_3OD): δ = 1.77–1.83 (m, 1 H, -C*H*$_2$CH$_2$OH), 2.03–2.08 (m, 1 H, -C*H*$_2$CH$_2$OH), 2.66 (d, J = 11.3 Hz, 1 H, -SCH$_2$-), 3.20 (dd, J = 11.3, 4.4 Hz, 1 H, -SCH$_2$-), 3.54–3.61 (m, 1 H, -SCH-), 3.62–3.69 (m, 2 H, -CH$_2$C*H*$_2$OH), 4.00 [t, J = 3.3 Hz, 1 H, -C*H*(OH)-], 4.26 [t, J = 2.0 Hz, 1 H, -C*H*(OH)-] ppm. ^{13}C NMR (100 MHz, CD_3OD): δ = 34.2 (-*C*H$_2$CH$_2$OH), 36.7 (-SCH$_2$-), 47.8 (-SCH-), 62.2 (-CH$_2$OH), 79.4 [-CH(OH)-], 80.1 [-CH(OH)-] ppm. HRMS: calcd. for $C_6H_{12}O_3SNa$ [M + Na]$^+$ 187.0405; found 187.0415.

6-Bromo-2,3,6-trideoxy-L-*threo*-hex-2-enono-1,4-lactone (13):[11] Butenolide **10** (4.13 g, 0.17 mol) was stirred with HCl (1 M in methanol; 110 mL, 0.11 mol) at 5 °C for 2 d. The reaction mixture was then concentrated in vacuo at 30 °C to give bromoalcohol **13** (3.28 g, 96%) as a gummy solid that was pure, and that was used in further reactions. IR (neat): $\tilde{\nu}$ = 3422, 1749, 1172, 1111, 1042, 849, 821, 616 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.48 (dd, J = 10.3, 6.2 Hz, 1 H, -CH$_2$Br), 3.58 (dd, J = 10.4, 6.6 Hz, 1 H, -CH$_2$Br), 4.07–4.12 [m, 1 H, -C*H*(OH)-], 5.38 (s, 1 H, -C*H*OCO-), 6.19 (d, J = 5.6 Hz, 1 H, -CH=C*H*COO-), 7.52 (d, J = 5.7 Hz, 1 H, -C*H*=CHCOO-) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 32.7 (-CH$_2$Br), 70.7 [-CH(OH)-], 83.5 (-*C*HOCO-), 122.7 (-CH=*C*HCOO-), 153.9 (-*C*H=CHCOO-), 173.2 [-OC(O)-] ppm.

Synthesis of Compound 14 from 13: $(BnEt_3N)_2MoS_4$, (**11**; 3.55 g, 5.8 mmol) was added to a solution of bromohydrin **13** (0.549 g, 2.65 mmol) in acetonitrile (20 mL), (Bnand the reaction mixture was stirred for 1 h. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The organic phase was concentrated to give the crude product, which, upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 1:1) gave a white solid. This solid was recrystallized from a mixture of hexanes and ethyl acetate to give sulfur compound **14** (0.365 g, 86%) as colorless crystals; m.p. 104–105 °C. $[\alpha]_D$ = +64.0 (c = 1.0, MeOH). IR (neat): $\tilde{\nu}$ = 3447, 1748, 1178, 1154, 1040, 1001, 692 cm^{-1}. ^{1}H NMR (400 MHz, [D$_6$]acetone): δ = 2.57 (d, J = 17.8 Hz, 1 H, -CH$_2$COO-), 2.88 (d, J = 11.7 Hz, 1 H, -CH$_2$COO-), 3.11 (dd, J = 17.8, 6.9 Hz, 1 H, -SCH$_2$-), 3.22 (dd, J = 11.7, 3.7 Hz, 1 H, -SCH$_2$-), 4.24 (d, J = 5.9 Hz, 1 H, -SCH-), 4.59 [d, J = 4.2 Hz, 1 H, -C*H*(OH)-], 4.70 (s, 1 H, -OH), 4.91 (d, J = 4.8 Hz, 1 H, -CHOCO-) ppm. ^{13}C NMR (100 MHz, [D$_6$]acetone): δ = 38.5 (-*C*H$_2$COO-), 39.4 (-SCH$_2$-), 45.8 (-SCH-), 77.3 [-CH(OH)-], 90.2 (-*C*HOCO-), 175.4 [-OC(O)-] ppm. HRMS: calcd. for $C_6H_8O_3SNa$ [M + Na]$^+$ 183.0092; found 183.0091. $C_6H_8O_3S$ (160.02): calcd. C 45.06, H 5.11, S 20.00; found C 44.99, H 5.03, S 20.02.

Crystal Structure Data: $C_6H_{10}O_4S$; M_r = 178.20; crystal dimensions: 0.25 × 0.23 × 0.16 mm; T = 291(2) K; orthorhombic; space group $P2_12_12_1$; a = 5.2242(5), b = 7.5040(7), c = 20.4727(19) Å; $\alpha = \beta = \gamma$ = 90.00°; Z = 4, V = 802.58(13) cm^3; $\rho_{calcd.}$ = 1.475 g cm^{-3}; Mo-K_α radiation (λ = 0.71073 Å); μ = 3.7.00 mm^{-1}; 2θ = 2.9–23.0°; of 8316 reflections collected, 1123 were independent [R(int) = 0.0413]; refinement method full-matrix least-squares on F^2, 109 refined parameters, absorption correction SADABS software, Bruker, 1996; T_{min} = 0.8376 and T_{max} = 0.9642; GooF = 1.063, R_1 = 0.0413, wR_2 = 0.0244 [$\sigma > 2\sigma(I)$]; absolute structure parameter: –0.09(9); residual electron density: 0.169/–0.106 e Å^{-3}.

5,6-Anhydro-2,3-dideoxy-L-*threo*-hex-2-enono-1,4-lactone (15): Ag_2O (0.56 g, 2.4 mmol) was added to a solution of compound **13** (0.5 g, 2.4 mmol) in water (2 mL) at 0 °C, and the mixture was stirred for 4 h at the same temperature. After completion of the reaction, HBr was added to precipitate AgBr. The mixture was filtered, and the precipitate was washed with CH_2Cl_2 (2 × 5 mL). The collected washings and filtrate were mixed together and extracted again with CH_2Cl_2 (3 × 5 mL). The combined organic extracts were dried with $MgSO_4$ and concentrated in vacuo below 30 °C to give **15** (0.213 g, 70%) as a low-melting white solid. IR (neat): $\tilde{\nu}$ = 1780,

1349, 1192, 1156, 1065, 1042, 893, 866 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.77 (dd, J = 4.6, 2.1 Hz, 1 H, -CH_2O-), 2.84 (dd, J = 4.7, 2.5 Hz, 1 H, -CH_2O-), 3.13 [d, J = 2.6 Hz, 1 H, -C(*H*)O-], 5.03 (t, J = 1.9 Hz, 1 H, -CHOCO-), 6.18 (dd, J = 5.6, 1.4 Hz, 1 H, -CH=C*H*COO-), 7.45 (d, J = 5.6 Hz, 1 H, -C*H*=CHCOO-) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 43.8 (-CH_2O-), 50.6 [-C(H)O-], 81.8 (-*C*HOCO-), 123.1 (-CH=*C*HCOO-), 152.0 (-*C*H=CHCOO-), 172.3 [-OC(O)-] ppm.

Synthesis of 14 from 15: $(BnEt_3N)_2MoS_4$ (**11**; 0.629 g, 2.7 mmol) was added to a stirred suspension of epoxy butenolide **15** (0.156 g, 1.2 mmol) in a mixture of acetonitrile (4 mL) and ethanol (4 mL), and the reaction mixture was stirred for 1 h. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The combined extracts were concentrated to give the crude product, which, upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 1:1) gave a white solid. This solid was recrystallized from a mixture of hexanes and ethyl acetate to give bicyclic lactone **14** (0.178 g, 90%) as colorless crystals.

Synthesis of Epoxide from Compound 6

Using KF: KF[17] (6.859 g, 0.118 mol) was added to 2,6-dibromo-2,6-dideoxy-L-gulonolactone (**6**; 6.9 g, 0.023 mol) in acetone (140 mL), and the mixture was stirred for 7 h at room temperature. The mixture was then filtered, and the organic layer was concentrated in vacuo to give a crude compound. Upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 1:1), this residue gave 6-bromo-2,3-monoepoxygulono-γ-lactone (five-membered ring lactone, i.e., **16**) along with the required 6-bromo-2,3-monoepoxygulono-δ-lactone (six-membered ring lactone, i.e., **17**) in a 2:3 ratio (3.594 g, 71%), as well an unidentified product. Compounds **16** and **17** were inseparable by column chromatography. IR (neat): $\tilde{\nu}$ = 3407, 1780, 1769, 1173, 1104, 1060, 1009, 910 cm^{-1}. HRMS: calcd. for $C_6H_7{}^{79}Br_2O_4Na$ $[M + Na]^+$ 244.9476; found 246.9478.

Using K_2CO_3: K_2CO_3 (23.7 g, 0.171 mol) was added to 2,6-dibromo-2,6-dideoxy-L-gulonolactone (**6**; 7.8 g, 0.026 mol) in acetone (160 mL), and the mixture was stirred for 5 h at room temperature. The mixture was then filtered, and the organic layer was concentrated in vacuo to give a crude compound. Upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 1:1), this residue gave the required 6-bromo-2,3-monoepoxygulono-δ-lactone (six-membered ring lactone) **17** along with 6-bromo-2,3-monoepoxygulono-γ-lactone (five-membered ring lactone) **16** in a 4:1 ratio (3.663 g, 64%). Epoxides **17** and **16** were inseparable by column chromatography.

Synthesis of the Bicyclic Lactone 18 from 6-Bromo-2,3-anhydrogulono-δ-lactone (six-membered ring lactone) 17: $(BnEt_3N)_2MoS_4$, (**11**; 4.2 g, 6.91 mmol) was added to a solution of 6-bromo-2,3-monoepoxygulono-δ-lactone **17** (0.7 g, 3 mmol) in a mixture of acetonitrile (10 mL) and ethanol (10 mL), and the reaction mixture was stirred for 4 h. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The combined extracts were concentrated to give a crude product, which, upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 1:1) gave a white solid. This was recrystallized from a mixture of hexanes and ethyl acetate to give bicyclic sulfur compound **18** (0.365 g, 66%) as colorless crystals; m.p. 178–179 °C. $[\alpha]_D$ = –44.0 (c = 1.0, MeOH). IR (neat): $\tilde{\nu}$ = 3350, 3339, 1734, 1527, 1156, 1038, 672 cm^{-1}. ^1H NMR (400 MHz, $[D_6]$acetone): δ = 2.99 (dd, J = 11.7, 3.8 Hz, 1 H, -SCH_2-), 3.22 (m, J = 20.7, 11.7 Hz, 2 H, -SCH_2- and -SCH-), 3.96 (br. s, 1 H), 4.15 (d, J = 2.1 Hz, 1 H), 4.87 (t, J = 4.1 Hz, 1 H), 5.03 (d, J = 4.5 Hz, 1 H), 5.10 (d, J = 3.4 Hz, 1 H, -CHOCO-) ppm. ^{13}C NMR (100 MHz, $[D_6]$acetone): δ = 23.2 (-SCH_2-), 40.6 (-SCH-), 73.9 [-CH(OH)-], 77.7 [-CH(OH)-], 78.0 (-*C*HOCO-), 169.3 [-OC(O)-] ppm. HRMS: calcd. for $C_6H_8O_4SNa$ $[M + Na]^+$ 199.0041; found 199.0039. $C_6H_8O_4S$ (176.01): calcd. C 40.9, H 4.58, S 18.2; found C 40.8, H 4.6, S 18.2.

Crystal Structure Data: $C_6H_8O_4S$; M_r = 176.18; crystal dimensions: 0.27 × 0.21 × 0.18 mm; T = 273(2) K; monoclinic, space group: $P2(1)$; a = 6.4978(8), b = 10.5423(13), c = 10.6323(13) Å; $\alpha = \gamma$ = 90.00, β = 91.712(2)°; Z = 4, V = 728.01(15) cm^3; $\rho_{calcd.}$ = 1.607 $g\,cm^{-3}$; Mo-K_α radiation (λ = 0.71073 Å); μ = 4.0 mm^{-1}; 2θ = 1.9–26.0°; of 3481 reflections collected, 2781 were independent [R(int) = 0.0133]; refinement method full-matrix least-squares on F^2, 263 refined parameters; absorption correction SADABS software, Bruker, 1996; T_{min} 0.9057 and T_{max} 0.9235, GooF = 1.036, R_1 = 0.0133, wR_2 = 0.0227 [$\sigma > 2\sigma(I)$]; absolute structure parameter: –0.01(5); residual electron density: 0.194/–0.229 e $Å^{-3}$.

Thio-deoxy-*ido*-nojirimycin 8a from Bicyclic Lactone 18: A solution of lactone **18** (0.3 g, 0.017 mol) in dry methanol (20 mL) was stirred at 0 °C with borohydride exchange resin (3.4 g, 0.010 mol) for 20 h. The reaction mixture was filtered, and methanol (10 mL) was added to the resin and was sonicated (ultrasonic cleaning bath, 20 kHz) for 5 min at room temperature. The sonicated reaction mixture was then neutralized using glacial acetic acid. The reaction mixture was filtered and concentrated in vacuo to give a crude product. This residue was subjected to column chromatography on silica gel (eluting with methanol/chloroform, 1.5:8.5) to give thio-deoxy-*ido*-nojirimycin **8a** (0.206 g, 67%) as a gummy solid. $[\alpha]_D$ = –35.0 (c = 1.0, MeOH). IR (neat): $\tilde{\nu}$ = 3448, 3444, 3410, 1699, 1526, 1253, 1169, 1033 cm^{-1}. ^1H NMR (400 MHz, D_2O): δ = 2.45 (dd, J = 13.8, 4.4 Hz, 1 H, -SCH_2-), 2.58 (t, J = 13.7 Hz, 1 H, -SCH_2-), 2.89–2.84 (m, 1 H, -SCH-), 3.23 (dd, J = 18.3, 9.1 Hz, 1 H, -CH_2OH), 3.58–3.53 (m, 1 H, -CH_2OH), 3.62 [t, J = 10.4 Hz, 1 H, -C*H*(OH)-], 3.82–3.80 [m, 1 H, -C*H*(OH)-], 3.87 [dd, J = 11.6, 4.0 Hz, 1 H, -C*H*(OH)-] ppm. ^{13}C NMR (100 MHz, D_2O): δ = 27.3 (-SCH_2-), 45.9 (-SCH-), 57.1 (-CH_2OH), 72.9 [-CH(OH)-], 73.6 [-CH(OH)-], 73.7 [-CH(OH)-] ppm. HRMS: calcd. for $C_6H_{12}O_4SNa$ $[M + Na]^+$ 203.0354; found 203.0356.

Acetonation of 2,6-Dibromo-2,6-dideoxy-L-idono-1,4-lactone (6): A solution of 2,6-dibromo-2,6-dideoxy-D-idono-1,4-lactone (**6**; 2.2 g, 6.58 mmol) in CH_2Cl_2 (8 mL) was stirred with 2,2-DMP (10.3 g, 0.0987 mol) and *p*TsOH (1.25 g, 6.58 mmol) at room temperature for 45 min. The reaction mixture was then stirred with solid K_2CO_3 (to quench *p*TsOH) for a few minutes. The mixture was then filtered through a Celite pad, and concentrated. The residue was purified by column chromatography on silica gel (eluting with hexanes/ethyl acetate, 8.5:1.5) to give the required compound (i.e., **19a**) as the major product, along with **19b** in a 3:1 ratio (**19a**: 1.26 g, 47%; **19b**: 0.43 g, 15%).

Compound 19a: IR (neat): $\tilde{\nu}$ = 3504, 1741, 1438, 1374, 1240, 1223, 1157, 1074, 880 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.45 [s, 3 H, -$C(CH_3)_2$-], 1.47 [s, 3 H, -$C(CH_3)_2$-], 2.70 (d, J = 8.0 Hz, 1 H, -OH), 3.48 (d, J = 6.7 Hz, 2 H, -CH_2Br), 3.82 (s, 3 H, -CO-OCH_3), 3.89–3.91 [m, 1 H, -CH(Br)-], 4.34 [dd, J = 6.9, 2.1 Hz, 1 H, -CH(O)-], 4.44 [d, J = 6.2 Hz, 1 H, -CH(O)-], 4.48 [d, J = 6.5 Hz, 1 H, -CH(O)-] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 27.1 [-$C(CH_3)_2$-], 27.2 [-$C(CH_3)_2$-], 34.0 (-CH_2Br), 45.8 [-CH(Br)-], 53.3 (-OCH_3), 69.9 [-C(H)O-], 77.3 [-C(H)O-], 78.5 [-C(H)O-], 111.0 [-O*C*$(CH_3)_2$O-], 167.9 [-OC(O)-] ppm. HRMS: calcd. for $C_{10}H_{16}Br_2O_5Na$ $[M + Na]^+$ 396.9262; found 396.9262.

Compound 19b: IR (neat): $\tilde{\nu}$ = 1790, 1386, 1201, 1178, 1096, 1032, 945, 870 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.41 [s, 3 H,

-C(CH_3)$_2$-], 1.50 [s, 3 H, -C(CH_3)$_2$-], 3.47 (dd, J = 10.1, 6.0 Hz, 1 H, -CH_2Br), 3.58 (dd, J = 10.1, 8.2 Hz, 1 H, -CH_2Br), 4.13 [s, 1 H, -CH(O)-], 4.30 [dt, J = 7.0, 1.8 Hz, 1 H, -CH(Br)-], 4.61 [d, J = 2.3 Hz, 1 H, -CH(O)-], 4.76 [d, J = 2.0 Hz, 1 H, -CH(O)-] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 19.3 [-C(CH_3)$_2$-], 28.5 [-C(CH_3)$_2$-], 29.1 (-CH_2Br), 40.3 [-CH(Br)-], 68.5 [-C(H)O-], 70.9 [-C(H)O-], 73.1 [-C(H)O-], 99.6 [-OC(CH_3)$_2$O-], 170.8 [-OC(O)-] ppm. HRMS: calcd. for $C_9H_{12}Br_2O_4Na$ [M + Na]$^+$ 364.9000; found 364.8999.

Synthesis of Deoxythiosugar Carboxylate 20 from Dibromo Ester 19a: A solution of dibromo ester **19a** (1.0 g, 2.66 mmol) in acetonitrile (20 mL) was stirred with $(BnEt_3N)_2MoS_4$ (**11**; 3.56 g, 5.86 mmol) for 1 h. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The combined extracts were concentrated to give the crude product. This residue was purified by column chromatography on silica gel (eluting with hexanes/ethyl acetate, 3:2) to give deoxythiosugar carboxylate **20** (0.554 g, 84%) as a gummy solid. IR (neat): $\tilde{\nu}$ = 3531, 1736, 1438, 1375, 1232, 1200, 1059, 982, 870 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.40 [s, 3 H, -C(CH_3)$_2$-], 1.42 [s, 3 H, -C(CH_3)$_2$-], 2.70 (dd, J = 18.0, 13.2 Hz, 1 H, -SCH_2-), 2.81 (dd, J = 18.0, 6.4 Hz, 1 H, -SCH_2-), 2.93 (s, 1 H, -OH), 3.21 [t, J = 12.4 Hz, 1 H, -CH(OH)-], 3.67 (d, J = 13.6 Hz, 1 H, -SCH-), 3.76 (s, 3 H, -OCH_3-), 3.94 [dd, J = 13.6, 12.0 Hz, 1 H, -C(H)O-], 4.04–4.07 [m, 1 H, -C(H)O-] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 26.6 [-C(CH_3)$_2$-], 26.8 [-C(CH_3)$_2$-], 33.8 (-SCH_2-), 47.0 (-SCH-), 52.9 (-OCH_3), 71.2 [-C(H)O-], 77.3 [-C(H)O-], 82.3 [-C(H)O-], 109.8 [-OC(CH_3)$_2$O-], 168.6 [-OC(O)-] ppm. HRMS: calcd. for $C_{10}H_{16}O_5SNa$ [M + Na]$^+$ 271.0616; found 271.0615.

Synthesis of Deoxythiosugar 21 from 20: Compound **20** (0.250 g, 1.0 mmol) was stirred with glacial acetic acid (8 mL) overnight. The mixture was then concentrated to give a crude product, which, upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 2:3) gave a white solid. This solid was recrystallized from hot $CHCl_3$ to give deoxythiosugar carboxylate **21** (0.205 g, 98%) as colorless crystals. $[\alpha]_D$ = +11.0 (c = 1.0, MeOH). IR (neat): $\tilde{\nu}$ = 3474, 1736, 1450, 1376, 1261, 1214, 1163, 1059, 878 cm^{-1}. ^{1}H NMR (400 MHz, CD_3OD): δ = 2.64–2.67 (m, 2 H, -SCH_2-), 3.12 [t, J = 9.0 Hz, 1 H, -CH(OH)-], 3.47 (d, J = 10.2 Hz, 1 H, -SCH-), 3.63 [dt, J = 9.2, 6.1 Hz, 1 H, -CH(OH)-], 3.73 (s, 3 H, -$COOCH_3$), 3.75 [dd, J = 15.4, 9.7 Hz, 1 H, -CH(OH)-] ppm. HRMS: calcd. for $C_7H_{12}O_5SNa$ [M + Na]$^+$ 231.0303; found 231.0301.

Crystal Structure Data: $C_7H_{12}O_5S$; M_r = 208.23; Crystal dimensions 0.50 × 0.16 × 0.12 mm; T = 296(2) K; orthorhombic; space group $P2_12_12_1$; a = 5.1274(2), b = 10.1735(4), c = 17.4541(9) Å; $\alpha = \beta = \gamma$ = 90.00°; Z = 4, V = 910.47(7) cm^3; $\rho_{calcd.}$ = 1.512 g cm^{-3}; Mo-K_α radiation (λ = 0.71073 Å); μ = 3.4 mm^{-1}; 2θ = 2.3–25.0°; of 1760 reflections collected, 1527 were independent [R(int) = 0.0324]; refinement method full-matrix least-squares on F^2, 123 refined parameters; absorption correction SADABS software, Bruker, 1996; T_{min} = 0.8470 and T_{max} = 0.9599; GooF = 1.144, R_1 = 0.0250, wR_2 = 0.0323 [$\sigma > 2\sigma(I)$]; absolute structure parameter: 0.06(10); residual electron density: 0.184/–0.161 e Å^{-3}.

Thio-deoxy-nojirimycin 8b: Compounds **20** and **21** were reduced by a procedure similar to the synthesis of thio-deoxy-*ido*-nojirimycin **8a**, to give thio-deoxy-nojirimycin **8b**; yield (0.142 g, 78%). $[\alpha]_D$ = +22.0 (c = 1.0, MeOH), lit.[4b] $[\alpha]_D$ = +50.0 (c = 1.39, H_2O). IR (neat): $\tilde{\nu}$ = 3358, 3349, 1581, 1403, 1120, 1017, 770, 671 cm^{-1}. ^{1}H NMR (400 MHz, CD_3OD): δ = 2.55–2.66 (m, 2 H, -SCH_2-), 2.79–2.84 (m, 1 H, -SCH-), 3.11 (t, J = 8.0 Hz, 1 H), 3.45 (t, J = 12.0 Hz, 1 H), 3.58 (ddd, J = 8.0, 4.0, 4.0 Hz, 1 H), 3.72 (dd, J = 12.0, 8.0 Hz, 1 H), 3.95 (dd, J = 12.0, 4.0 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, CD_3OD): δ = 31.8, 48.2, 61.4, 73.3, 74.4, 79.3 ppm. HRMS: calcd. for $C_6H_{12}O_4SNa$ [M + Na]$^+$ 203.0354; found 203.0354.

5,6-Di-*O*-acetyl-7-bromo-2,3,7-trideoxy-D-arabino-hept-2-enono-1,4-lactone (25): $Na_2S_2O_5$ (2.57 g, 0.013 mol) was added to a solution of 3,5,6-tri-*O*-acetyl-2,7-dibromo-2,7-dideoxy-D-*glycero*-D-*ido*-heptono-1,4-lactone (**24**; 12.20 g, 0.027 mol) in MeOH (54 mL) and H_2O (7 mL). Na_2SO_3 (7.02 g, 0.056 mol) was then added in portions, and stirring was continued for 3.5 h at room temperature. The reaction mixture was quenched with HCl (1 N, 87 mL), and the product was extracted with CH_2Cl_2 (4 × 50 mL). The combined organic extracts were dried ($MgSO_4$), filtered and evaporated to give a pale yellow solid. The solid was subjected to a short column chromatography to give 5,6-di-*O*-acetyl-7-bromo-2,3,7-trideoxy-D-*arabino*-hept-2-enono-1,4-lactone (**25**; 81%) as a cream-colored solid; m.p. 151.5–153.5 °C. $[\alpha]_D$ = +84.0 (c = 1, MeOH). IR (neat): $\tilde{\nu}$ = 1759, 1745, 1426, 1372, 1216, 1192, 1020, 833 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.04 (s, 3 H, -$OCOCH_3$), 2.16 (s, 3 H, -$OCOCH_3$), 3.53 (dd, J = 4.5, 12.0 Hz, 1 H, -CH_2Br), 3.86 (dd, J = 4.0, 16.0 Hz, 1 H, -CH_2Br), 5.31–5.37 [m, 2 H, -C(H)OCO- and -CH(OCOCH_3)-], 5.43 [dd, J = 7.8, 1.5 Hz, 1 H, -CH(OCOCH_3)-], 6.15 (dd, J = 5.7, 2.1 Hz, 1 H, -CH=CHCOO-), 7.41 (dd, J = 5.7, 1.8 Hz, 1 H, -CH=CHCOO-) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 20.4 (-OCOCH$_3$), 20.7 (-OCOCH$_3$), 31.1 (-CH_2Br), 69.2 [-C(H)O-], 70.1 [-C(H)O-], 80.6 [-C(H)O-], 122.6 (-CH=CHCOO-), 152.39 (-CH=CHCOO-), 169.3 [-OC(O)-], 169.5 [-OC(O)-], 171.8 [-OC(O)-] ppm.

2,3-Di-*O*-acetyl-1,5-anhydro-6-deoxy-5-thio-L-*gulo*-heptono-4,7-lactone (26): $(BnEt_3N)_2MoS_4$, (**11**; 9.73 g, 0.016 mol) was added to a solution of 5,6-di-*O*-acetyl-7-bromo-2,3,7-trideoxy-D-*arabino*-hept-2-enono-1,4-lactone (**25**; 2.332 g, 7.262 mmol) in CH_3CN (30 mL), and the mixture was stirred for 5 h at room temperature. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The combined extracts were concentrated to give a crude product, which upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 1:1) gave a white solid. This solid was recrystallized from a mixture of hexanes and ethyl acetate to give 1,6-dideoxy-2,3-diacetoxy-5-thio-L-gulono-4,7-lactone (**26**; 1.33 g, 67%) as colorless crystals; m.p. 124–126 °C. IR (neat): $\tilde{\nu}$ = 1792, 1746, 1373, 12320, 1040 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.07 (s, 3 H, -$COCH_3$), 2.15 (s, 3 H, -$COCH_3$), 2.42 (dd, J = 3.0, 17.5 Hz, 1 H, -CH_2COO-), 2.66 (dd, J = 3.9, 13.6 Hz, 1 H, -CH_2COO-), 2.85 (dd, J = 6.7, 17.5 Hz, 1 H, -SCH_2-), 3.06 (dd, J = 8.6, 13.6 Hz, 1 H, -SCH_2-), 3.84 (q, J = 3.4 Hz, 1 H, -SCH-), 4.66 (t, J = 4.9 Hz, 1 H, -CHOCO-), 5.33–5.39 [m, 2 H, -CH(OCOCH_3)-] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.7 (-OCOCH$_3$), 20.9 (-OCOCH$_3$), 25.4 (-CH$_2$COO-), 35.3 (-SCH_2-), 35.9 (-SCH-), 67.7 [-C(H)O-], 68.1 [-C(H)O-], 78.4 [-C(H)O-], 169.4 [-OC(O)-], 169.6 [-OC(O)-], 173.2 [-OC(O)-] ppm. HRMS: calcd. for $C_{11}H_{14}O_6SNa$ [M + Na]$^+$ 297.0409; found 297.0404.

Thio-homo-deoxy-*gulo*-nojirimycin 27: Gummy solid. ^{1}H NMR (400 MHz, CD_3OD): δ = 1.67 (sept, J = 6.2 Hz, 1 H, -CH_2CH$_2$OH), 1.80 (sept, J = 6.7 Hz, 1 H, -CH_2CH$_2$OH), 2.28 (d, J = 12.6 Hz, 1 H, -SCH_2-), 2.92 (t, J = 12.3 Hz, 1 H, -SCH_2-), 3.35 (t, J = 7.4 Hz, 1 H, -SCH-), 3.59–3.69 (m, 2 H, -CH_2OH), 3.79 [s, 1 H, -CH(OH)-], 3.87 [s, 1 H, -CH(OH)-], 4.03 [d, J = 10.6 Hz, 1 H, -CH(OH)-] ppm. ^{13}C NMR (100 MHz, CD_3OD): δ = 27.4 (-CH$_2$CH$_2$OH), 33.0 (-SCH_2-), 37.1 (-SCH-), 59.1 (-CH_2OH), 67.1 [-C(H)O-], 71.9 [-C(H)O-], 72.7 [-C(H)O-] ppm.

1-Deoxy-5-thio-L-gulono-4,7-lactone (30): Gummy solid; $[\alpha]_D$ = –116.0 (c = 1, MeOH). IR (neat): $\tilde{\nu}$ = 3409, 1779, 1652, 1417, 1385,

1116, 1023, 990, 749 cm^{-1}. ^{1}H NMR (300 MHz, [D$_6$]acetone): δ = 2.28 (dt, J = 3.9, 13.1 Hz, 2 H, -CH$_2$COO-), 2.90–3.05 (m, 2 H, -SCH$_2$-), 3.83 (sept, J = 1.9 Hz, 1 H, -SCH-), 3.94 [td, J = 3.9, 9.9 Hz, 1 H, -C*H*(OH)-], 4.02 [d, J = 2.1 Hz, 1 H, -C*H*(OH)-], 4.68 (d, J = 4.5 Hz, 1 H, -CHOCO-) ppm. ^{13}C NMR (75 MHz, [D$_6$]acetone): δ = 27.2 (-*C*H$_2$COO-), 35.6 (-SCH$_2$-), 37.7 (-SCH-), 68.4 [-C(H)O-], 68.9 [-C(H)O-], 83.8 [-C(H)O-], 177.3 [-OC(O)-] ppm. HRMS: calcd. for C$_7$H$_{10}$O$_4$SNa [M + Na]$^+$ 213.0198; found 213.0192.

Synthesis of Epoxy Butenolide 29: Silver oxide (2.07 g, 8.932 mmol) was added to a solution of lactone **28** (0.8 g, 3.375 mmol) in toluene (15 mL), and the mixture was heated at 80 °C under an atmosphere of N$_2$. The mixture was then filtered and concentrated to give a syrupy liquid. This residue was subjected to column chromatography on silica gel (eluting with EtOAc/hexanes, 1:1) to give epoxide **29** (0.299 g, 56%) as a gummy compound. [a]$_D$ = +78.0 (c = 1, MeOH). IR (neat): $\tilde{\nu}$ = 3451, 1752, 1638, 1172, 1042, 828 cm^{-1}. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 2.81 (dd, J = 2.4, 4.8 Hz, 1 H, -CH$_2$O-), 2.89 (dd, J = 4.2, 4.8 Hz, 1 H, -CH$_2$O-), 3.18 [m, 1 H, -C(*H*)O-], 3.71 [m, 2 H, -C(*H*)O-], 5.24 (tt, J = 1.5, 2.1 Hz, 1 H, -CHOCO-), 6.22 (dd, J = 2.1, 5.7 Hz, 1 H, -CH=C*H*COO-), 7.56 (dd, J = 2.1, 6.0 Hz, 1 H, -C*H*=CHCOO-) ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 45.5 (-CH$_2$O-), 51.1 [-C(H)O-], 71.1 [-C(H)O-], 84.1 [-C(H)O-], 122.6 (-CH=*C*HCOO-), 153.3 (-*C*H=CHCOO-), 173.1 [-OC(O)-] ppm. HRMS: calcd. for C$_7$H$_8$O$_4$Na [M + Na]$^+$ 179.0320; found 179.0320.

Acetonide Protection of Dibromoheptonolactone 23: A solution of dibromoheptonolactone **23** (16.957 g, 0.05 mol) in CH$_2$Cl$_2$ (100 mL) was stirred with 2,2-DMP (6.346 g, 0.061 mol) and *p*TsOH (1.932 g, 0.01 mol) at room temperature for 45 min. The mixture was then stirred with solid K$_2$CO$_3$ (to quench the *p*TsOH) for a few minutes, and then it was filtered through a Celite pad and concentrated. The residue was purified by column chromatography on silica gel (eluting with hexanes/ethyl acetate, 8.5:1.5) to give dibromide **31** (8.69 g, 46%) and **32** (4.34 g, 23%), formed in a 2:1 ratio.

Isopropylidene Lactone 31: IR (neat): $\tilde{\nu}$ = 873, 1046, 1121, 1184, 1385, 1789, 2995, 3484 cm^{-1}. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 1.39 [s, 3 H, -C(CH$_3$)$_2$-], 1.49 [s, 3 H, -C(CH$_3$)$_2$-], 2.81 (d, J = 5.4 Hz, 1 H, -OH), 3.68 (s, 2 H, -CH$_2$Br), 4.11 [d, J = 9.9 Hz, 3 H, -CH(Br)- and -C(*H*)O-], 4.56 [d, J = 2.1 Hz, 1 H, -C(*H*)O-], 4.82 (s, 1 H, -CHOCO-) ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 19.3 [-C(*C*H$_3$)$_2$-], 28.8 [-C(*C*H$_3$)$_2$-], 37.8 (-CH$_2$Br), 40.6 [-CH(Br)-], 68.3 [-C(H)O-], 69.2 [-C(H)O-], 70.9 [-C(H)O-], 73.4 [-C(H)O-], 99.3 [-O*C*(CH$_3$)$_2$O-], 171.3 [-OC(O)-] ppm.

Isopropylidene Ester 32: IR (neat): $\tilde{\nu}$ = 877, 1061, 1161, 1215, 1382, 1744, 2988 cm^{-1}. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 1.385 [s, 3 H, -C(CH$_3$)$_2$-], 1.424 [s, 3 H, -C(CH$_3$)$_2$-], 1.459 [s, 3 H, -C(CH$_3$)$_2$-], 1.518 [s, 3 H, -C(CH$_3$)$_2$-], 3.63 (d, J = 6.3 Hz, 2 H, -CH$_2$Br), 3.82 (s, 3 H, -COOCH$_3$), 4.27 [dd, J = 7.2, 12.6 Hz, 2 H, -CH(Br)- and -C(*H*)O-], 4.42–4.49 [m, 2 H, -C(*H*)O-], 4.55 [dd, J = 6.6, 13.5 Hz, 1 H, -C(*H*)O-] ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 25.2 [-C(*C*H$_3$)$_2$-], 26.6 [-C(*C*H$_3$)$_2$-], 26.9 [-C(*C*H$_3$)$_2$-], 27.1 [-C(*C*H$_3$)$_2$-], 30.4 (-CH$_2$Br), 45.4 [-CH(Br)-], 53.2 (-COO*C*H$_3$), 75.1 [-C(H)O-], 76.8 [-C(H)O-],109.5 [-O*C*(CH$_3$)$_2$O-], 110.8 [-O*C*(CH$_3$)$_2$O-], 167.8 [-OC(O)-] ppm.

Methyl 1-Thiepane-2-carboxylate Derivative 34: A solution of dibromo ester **32** (1.0 g, 2.24 mmol) in acetonitrile (25 mL) was stirred with (BnEt$_3$N)$_2$MoS$_4$, (**11**; 3.0 g, 4.93 mmol) for 5 h at room temperature. The mixture was then concentrated in vacuo, and the residue was repeatedly extracted with THF (5 × 5 mL). The combined extracts were concentrated to give a crude product, which, upon column chromatography on silica gel (eluting with hexanes/ethyl acetate, 3:2) gave thioseptanose derivative **34** (0.628 g, 80%) as a pale yellow solid; m.p. 140–142 °C. IR (neat): $\tilde{\nu}$ = 2988, 1743, 1381, 1260, 1232, 1215, 1161, 1048, 876 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.38 [s, 3 H, -C(CH$_3$)$_2$-], 1.44 [s, 3 H, -C(CH$_3$)$_2$-], 1.46 [s, 3 H, -C(CH$_3$)$_2$-], 1.52 [s, 3 H, -C(CH$_3$)$_2$-] 2.81–2.87 (m, 2 H, -SCH$_2$-), 3.55 (d, J = 7.3 Hz, 1 H, -SCH-), 3.66 [t, J = 3.4 Hz, 1 H, -C(*H*)O-], 3.79 (s, 3 H, -COOCH$_3$), 3.96 [t, J = 8.8 Hz, 1 H, -C(*H*)O-], 4.15 [dd, J = 9.2, 18.6 Hz, 1 H, -C(*H*)O-], 4.37 [dd, J = 7.1, 15.6 Hz, 1 H, -C(*H*)O-], 4.44–4.52 [m, 1 H, -C(*H*)O-] ppm. ^{13}C NMR (100 MHz, CDCl$_3$): δ = 24.4 [-C(*C*H$_3$)$_2$-], 26.7 [-C(*C*H$_3$)$_2$-], 27.0 [-C(*C*H$_3$)$_2$-], 27.3 [-C(*C*H$_3$)$_2$-], 30.6 (-SCH$_2$-), 49.7 (-SCH-), 52.9 (-COO*C*H$_3$), 76.7 [-C(H)O-], 78.4 [-C(H)O-], 78.6 [-C(H)O-], 79.6 [-C(H)O-], 109.9 [-O*C*(CH$_3$)$_2$O-], 110.3 [-O*C*(CH$_3$)$_2$O-], 169.3 [-OC(O)-] ppm. HRMS: calcd. for C$_{14}$H$_{22}$O$_6$SNa [M + Na]$^+$ 341.1035; found 341.1019.

Thiosugar 36: Gummy solid. [a]$_D$ = –69.0 (c = 1, CHCl$_3$). IR (neat): $\tilde{\nu}$ = 3422, 1778, 1095, 1068, 752, 699 cm^{-1}. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 2.31–2.49 (m, 1 H), 2.79 (dd, J = 17.1, 6.3 Hz, 1 H), 2.99 (dd, J = 13.2, 9.3 Hz, 1 H), 3.81 (t, J = 4.5 Hz, 1 H), 3.89 (t, J = 3.5 Hz, 1 H), 4.11–4.15 (m, 1 H), 4.66–4.77 (m, 1 H), 7.26–7.41 (m, 5 H) ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 27.8, 35.1, 36.4, 66.8, 73.7, 76.2, 80.0, 127.9, 128.3, 128.7, 137.3, 174.2 ppm.

Synthesis of Sugar Mesylate 37: Gummy solid. [a]$_D$ = –45.0 (c = 1, CHCl$_3$). ^{1}H NMR (300 MHz, CDCl$_3$): δ = 2.33 (d, J = 18.3 Hz, 1 H, -CH$_2$COO-), 2.65 (dd, J = 13.2, 3.6 Hz, 1 H, -CH$_2$COO-), 2.82 (dd, J = 17.7, 6.3 Hz, 1 H, -SCH$_2$-), 3.00 (s, 3 H, -SO$_2$CH$_3$), 3.04 (dd, J = 17.7, 9.3 Hz, 1 H, -SCH$_2$-), 3.94 (t, J = 5.1 Hz, 1 H, -SCH-), 4.10 [m, 1 H, -C(*H*)O-] 4.64–4.68 (m, 2 H, -OC*H*$_2$Ph), 4.83 [t, J = 4.2 Hz, 1 H, -C(*H*)O-], 5.09 [dd, J = 5.1, 2.1 Hz, 1 H, -C(*H*)O-], 7.27–7.37 (m, 5 H, -C$_6$H$_5$) ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 26.2, 35.1, 36.3, 38.5, 74.0, 74.1, 80.4, 128.1, 128.3, 128.6, 136.9, 173.5 ppm.

Azidation of Sugar Mesylate 37: A solution of sugar mesylate **37** (0.411 g, 1.15 mmol) in DMF (15 mL) was treated with NaN$_3$ (0.447 g, 6.88 mmol) at 80 °C, and stirred for 2 h. After completion of the reaction, the solvent was evaporated under vacuum, and the residue was partitioned between water (10 mL) and EtOAc (3 × 5 mL). The combined organic extracts were concentrated, dried (Na$_2$SO$_4$), and purified by column chromatography on silica gel to give azido lactones **38** and **39** in a 1:1 ratio (**38**: 0.089 g, 26%; **39**: 0.089 g, 26%) as gummy solids.

Azide 38: [a]$_D$ = –88.0 (c = 1, MeOH). IR (neat): $\tilde{\nu}$ = 2106, 1785, 1255, 1161, 1096, 1003, 751, 699 cm^{-1}. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 2.42–2.54 (m, 2 H, -CH$_2$COO-), 2.64–2.73 (m, 2 H, -SCH$_2$-), 3.34 (dd, J = 9, 7.2 Hz, 1 H, -SCH-), 3.57–3.70 [m, 2 H, -CH(N$_3$)- and -C(*H*)O-], 4.68 [t, J = 7.2 Hz, 1 H, -C(*H*)O-], 4.75 (d, J = 8.1 Hz, 1 H, -OC*H*$_2$Ph), 4.86 (d, J = 8.1 Hz, 1 H, -OC*H*$_2$Ph), 7.19–7.36 (m, 5 H, -C$_6$H$_5$) ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 26.9 (-*C*H$_2$COO-), 33.6 (-SCH$_2$-), 37.2 (-SCH-), 61.8 [-CH(N$_3$)-], 75.0 [-C(H)O-], 80.5 [-C(H)O-], 82.8 [-C(H)O-], 128.2 (-C$_6$H$_5$), 128.4 (-C$_6$H$_5$), 128.5 (-C$_6$H$_5$), 136.9 (-C$_6$H$_5$), 173.5 [-OC(O)-] ppm. HRMS: calcd. for C$_{14}$H$_{15}$N$_3$O$_3$SNa [M + Na]$^+$ 328.0732; found 328.0724.

Azide 39: IR (neat): $\tilde{\nu}$ = 2102, 1788, 1455, 1360, 1165, 1136, 1066, 1038, 985, 738, 698 cm^{-1}. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 2.64 (d, J = 18.3 Hz, 1 H, -CH$_2$COO-), 2.87 (dd, J = 17.7, 7.2 Hz, 1 H, -CH$_2$COO-), 3.43–3.61 (m, 2 H, -CH$_2$N$_3$), 3.70–3.76 (m, 1 H, -SCH-), 4.13–4.20 (m, 1 H, -SCH-), 4.33 [br. s, 1 H, -C(*H*)O-], 4.60 (s, 2 H, -OC*H*$_2$Ph), 4.85–4.88 [m, 1 H, -C(*H*)O-], 7.20–7.31 (m, 5 H, -C$_6$H$_5$) ppm. ^{13}C NMR (75 MHz, CDCl$_3$): δ = 25.2, 34.9, 36.3, 38.5, 72.0, 73.1, 79.5, 127.9, 128.3, 128.6, 136.9, 173.1 ppm.

HRMS: calcd. for $C_{14}H_{15}N_3O_3SNa$ $[M + Na]^+$ 328.0732; found 328.0722.

The structures were solved and refined with the programs WinGXv1.64.05, Sir92, and SHELXL-97. CCDC-802218 (for **14**), -802219 (for **21**), and -802220 (for **18**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Supporting Information (see footnote on the first page of this article): Common synthetic procedures adopted. NMR spectra of the compounds synthesized.

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