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cis-Fused bicyclic sugar thiocarbamates. Reactivity towards amines

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ABSTRACT

1,2-cis-Fused bicyclic sugar thiocarbamates of *gluco* and *manno* configurations have been prepared by treatment of the corresponding *O*-unprotected amino sugars and glycopyranosyl amines with thiophosgene. The reactivity of these compounds towards amines has been studied in order to determine whether these compounds could act as latent isothiocyanates; it is shown that 1,2-cis-fused bicyclic sugar thiocarbamates are more stable than their trans analogues, and are not transformed into thioureas upon treatment with amines. An unprecedented isomerization of a peracetylated glucopyranoso[2,1-*d*]oxazolidine-2-thione into a glucopyranoso[2,1-*d*]thiazolidin-2-one in DMF is also reported. The structure of this thiazolidin-2-one was confirmed by X-ray crystallography.

1. Introduction

Five- and six-membered cyclic thiocarbamates and carbamates (1,3-oxazolidine- and oxazinane-2-ones and 2-thiones) are important structural motifs in organic chemistry.[1] Some compounds bearing these structures have been reported to exhibit interesting biological effects,[2] including fructose transport inhibition,[3] antitumour,[4] and clinically useful antibacterial activity.[5] Oxazolidine-2-thiones obtained by enzyme-mediated hydrolysis of glucosinolates present in crucifer plants are known to cause goitre.[6] Furthermore, bicyclic trans-fused sugar carbamates have been described as detoxificant products upon interaction of plants with phytotoxic allelochemicals.[7]

From a synthetic point of view, the use of chiral 1,3-oxazolidine-2-thiones has emerged as a promising area in asymmetric synthesis, as these heterocycles are structurally related to Evans oxazolidinones.[8] In this context, chiral cyclic carbamates and thiocarbamates have been synthesized and used in Diels–Alder[9] and inverse hetero-Diels–Alder[10] reactions, in the preparation of β-lactam derivatives,[11] and in aldol condensations,[12] an important tool for the total synthesis of biologically active compounds.[13]

Sugar-derived oxazolidine-2-thiones have been recently used in desulfurative Sonogashira cross-coupling reactions with alkynes.[14] 2-*N*-3-*O*-Carbamate protected glucosamine donors have been used in glycosylation procedures,[15] and some bicyclic 5/5-cis-fused sugar thiocarbamates have been used in the preparation of nucleoside derivatives.[16] Bicyclic 5/5 and 5/6-fused thiocarbamates and carbamates are also interesting from a conformational point of view, and some theoretical calculations have been made,[17] together with X-ray diffraction studies.[18]

A classical procedure for the preparation of fused glycofurano and glycopyrano oxazolidin-2-one and -2-thione scaffolds consists of treatment of *O*-unprotected reducing sugars with KNCO[19] or KNCS,[20] respectively, in acidic medium. Kovács et al. have also reported the preparation of fused bicyclic sugar carbamates by Staudinger reaction of the corresponding glycopyranosyl azides with triphenylphosphane, followed by treatment with carbon dioxide.[21] Rollin's group has extensively studied the synthesis of spiranic and fused 1,3-oxazolidine-2-thiones by treatment of α-hydroxyketones,[22] ulosides[23] or ketohexose backbones[24] with thiocyanic acid. Carbohydrate-derived 1,3-oxazolidine- and 1,3-oxazinane-2-thiones can also be accessed when an isothiocyanate and a hydroxyl group are simultaneously present in the molecule,[25] depending on the relative arrangement of both functional groups, and thus, on the inherent strain of the cyclic moiety.[1,26]

We have previously reported[27] the preparation of fully unprotected β-D-glycopyranosyl isothiocyanates **3**,**4** of *gluco* and *galacto* configurations in equilibrium with the corresponding thiocarbamates **5**,**6** by isothiocyanation reaction of glycopyranosyl amines **1** and **2** with thiophosgene. These isothiocyanates were

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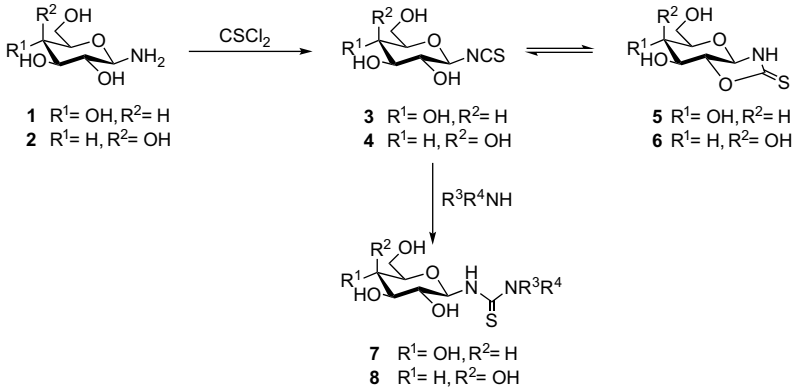


Scheme 1.

one-pot transformed into thioureas **7** and **8** upon treatment with aliphatic and aromatic amines (Scheme 1). Furthermore, 1,2-*trans*-fused glycopyranosyl carbamates, isosters of **5** and **6**, have been used in the preparation of urea-tethered neoglycoconjugates and pseudooligosaccharides upon reaction with different amines.[28,29]

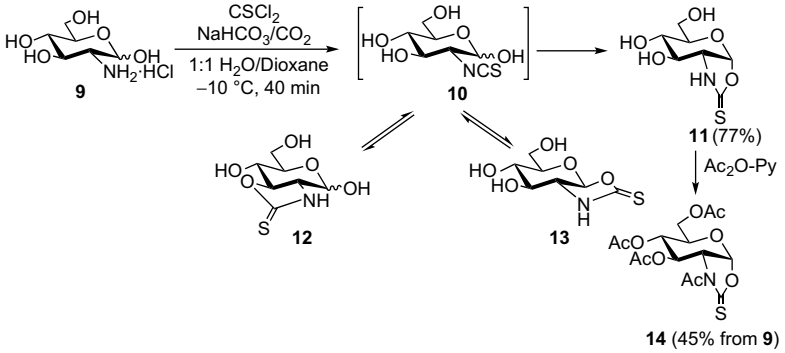
2. Results and discussion

We now report the synthesis of sugar-derived 1,2-cis-fused bicyclic thiocarbamates by treatment of *O*-unprotected amino sugars (2-amino-2-deoxy-D-glucose and -D-mannose) and β-D-mannopyranosylamine with thiophosgene in an aqueous buffered medium; the regioselectivity in the formation of these bicyclic sugar-containing structures has been studied.

cis-Fused bicyclic thiocarbamate **11** was prepared starting from 2-amino-2-deoxy-D-glucose hydrochloride **9** and thiophosgene in buffered aqueous dioxane (Scheme 2), in similar conditions as those previously described by us for the preparation of glycopyranosyl isothiocyanates **3** and **4**.[27] Thiocarbamate **11** was obtained in a 77% yield after column chromatography purification and underwent appreciable decomposition after storage at 0 °C for several days. The formation of this compound must take place through non-detected isothiocyanate **10**, followed by nucleophilic attack of the axial hydroxyl group of the α-anomer on the isothiocyanate group. ^{1}H and ^{13}C NMR spectra showed no equilibrium between cis-fused thiocarbamate **11** and isothiocyanate **10**, in contrast with our reported data[27,30] on trans-fused bicyclic thiocarbamates, which are in a solvent-dependent equilibrium with the corresponding isothiocyanate, as a result of the strain in the ring fusion of these fused five-membered–six-membered hydrindane-type systems.[31] This suggests that these cis-fused thiocarbamates are more stable that their trans-fused analogues, so the former do not undergo ring opening.

If annelation had taken place through hydroxyl group on C-3 or through equatorial hydroxyl group of the β-anomer, less stable trans-fused thiocarbamates **12** or **13** would have been obtained, respectively. Their equilibrium with isothiocyanate **10** would lead to the irreversible formation of **11**, as deduced by its NMR spectra. Vicinal coupling constants of thiocarbamate **11**, $J_{1,2}$ 6.8 Hz, $J_{2,3}$ 5.2 Hz, $J_{3,4}$ 5.3 Hz and $J_{4,5}$ 9.1 Hz, show a distorted pyranose ring for this compound, suggesting the preferential participation of a boat conformation[32] ($^{0,3}B$) rather than the $^{0}S_{2}$ pyranose conformation (Fig. 1) previously reported for structurally related bicyclic glycopyrano structures in solution.[18,21b,32,33]

Thiocarbamate **11** was conventionally acetylated (Ac_2O–Py)[34] to afford tetra-acetylated derivative **14**, which was crystallized from EtOH (Scheme 2). In order to study the behaviour of thiocarbamate **14** towards amines, compound **14** was treated with *p*-toluidine (2.0 equiv) in EtOH at 65 °C (Scheme 3). After 13 h at this temperature, *N*-deacetylated derivate **15** was isolated as the sole product in a 78% yield after chromatographic purification. NMR spectrum of the crude reaction also showed the formation of *N*-*p*-tolylacetamide. This transamidation could be explained considering that the conjugation of the lone pair electrons on the nitrogen atom with the C=S and C=O groups makes the carbonyl more electrophile, so the NAc group can react even with poor nucleophilic amines such as *p*-toluidine in contrast with the OAc groups.



Scheme 2.

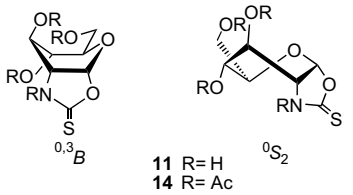
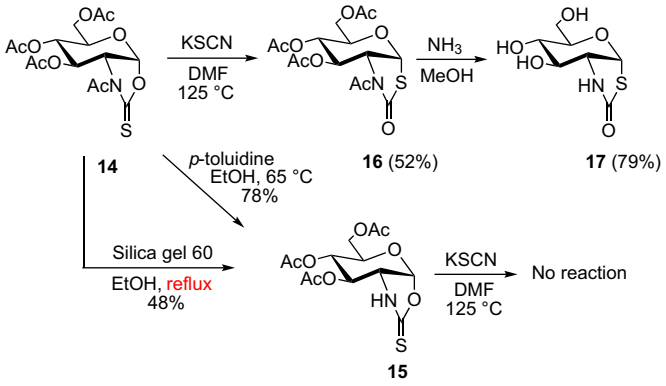


Figure 1.



Scheme 3.

It is remarkable that the extra equivalent of *p*-toluidine did not react with the *N*-deacetylated derivative **15** to give the corresponding thiourea; this result shows that cis-fused bicyclic thiocarbamates do not act as latent isothiocyanates in reactions with amines, in contrast with our results with their analogues trans-fused counterparts.[27,30] Derivative **15** was also obtained, although in a lower yield (48%), by ethanolysis of **14** at reflux under mild acidic conditions in the presence of silica gel (Scheme 3).

Both thiocarbamates **14** and **15** show the same conformational preference as compound **11**; the long-range coupling constant found for thiocarbamate **14** ($^4J_{2,4}$=0.8 Hz) indicates a W pathway between protons H-2 and H-4, what agrees with the major $^{0,3}B$ conformation in solution. A strong deshielding of the *N*Ac group (ca. 0.7 ppm) compared to acetate signals (2.09–2.00 ppm), and a strong deshielding of H-3 (ca. 0.5 ppm) in **14** compared with **15**, can be explained considering the two possible rotamers of the acetamido group (Fig. 2). *s-cis* Rotamer is unfavoured as a result of the repulsion between the dipoles of the carbonyl and thiocarbonyl groups.[35] This repulsion is reduced in *s-trans* rotamer; the thiocarbonyl provokes the deshielding of the methyl group and the carbonyl group the deshielding of H-3, observed in the ^{1}H NMR spectrum of **14** and in agreement with the behaviour of sugar-derived *N*-acetylated imidazolidine-2-thiones and oxazolidin-2-ones.[33,36]

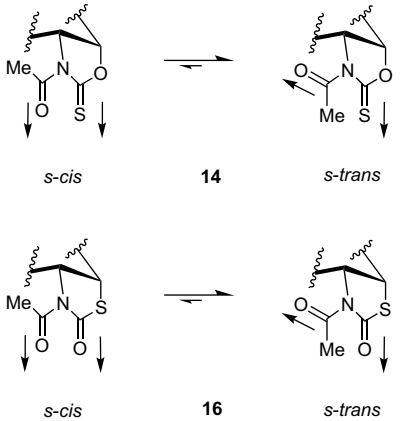


Figure 2.

We attempted the opening of the thiocarbamate moiety of compound **14** with several nucleophiles: with sodium azide in DMF at 100 °C **14** readily decomposed; however, with KSCN in DMF at 125 °C an unexpected isomerization into glucopyranoso[2,1-*d*]thiazolidin-2-one **16** took place (Scheme 3). Chromatographic purification afforded **16** with a 52% yield. It is remarkable that, to our knowledge, the only similar isomerization described in the literature implies an isomerization of a cytidine 2′,3′-thionocarbonate into a 2′-thiocytidine 2′,3′-carbonate at elevated temperature.[37] The only examples of bicyclic glyco-thiazolidin-2-ones previously reported are glycopyranoso[1,2-*d*]thiazolidin-2-ones prepared by Santoyo et al.[38] from 2-deoxy-2-iodoglycosyl isothiocyanates. Recently, bicyclic glycopyrano-thiazolines have been reported as potent and selective *O*-GlcNAcase inhibitors.[32,39] The isomerization must involve the opening of the thiocarbamate moiety with the formation of a transient oxocarbenium ion and cyclization through the more nucleophile sulfur atom on the anomeric carbon. In the absence of KSCN under the same time and temperature conditions, only a small amount of thiazolidin-2-one **16** was detected together with starting material and several decomposition products. Participation of nucleophilic thiocyanate anion in the opening of the thiocarbamate and the formation of the non-detected glycopyranosyl isothiocyanate or thiocyanate cannot be disregarded.[40]

When this reaction was carried out on *N*-deacetylated oxazolidine-2-thione **15** under the same reaction conditions, no isomerization took place; the reason might be that the higher electron density on the nitrogen atom, as compared with **14**, provokes a lower electron-withdrawing effect of the thiocarbonyl group by cross conjugation, and higher electron density on the anomeric oxygen atom, thus becoming a worse leaving group.

The slightly distorted $^4C_1$ conformation of thiazolidin-2-one **16** was deduced by the coupling constants found in the ^{1}H NMR spectrum ($J_{1,2}$ 6.7 Hz, $J_{2,3}$ 8.2 Hz, $J_{3,4}$ 9.4 Hz and $J_{4,5}$ 9.5 Hz). The conformational behaviour of **16** differs from that of oxazolidine-2-thiones **11**, **14** and **15**, which exhibit the $^{0,3}B$ conformation as the major one in solution. This boat conformation is also found for an unprotected bicyclic cis-fused GlcNAc-thiazoline, a potent transition-state-mimicking inhibitor of β-*N*-acetylglycosaminidases.[32] In contrast, GalNAc-thiazoline adopts the pseudo-chair $^4C_1$ in solution and in solid state;[39a] furthermore, GlcNAc-thiazoline binds in BtGH84 enzyme active site in a slightly distorted chair $^4C_1$ conformation.[41] The longer bonds of the sulfur atom compared to oxygen might explain the stability of the chair conformation for the pyranose ring in these bicyclic systems.

As observed for compound **14**, ^{1}H NMR and ^{13}C NMR spectra of **16** showed a deshielding (ca. 0.35 and 4.8 ppm, respectively) of the *N*Ac group with respect to the acetate groups, in accordance with the *s-trans* conformation (Fig. 2). Bicyclic thiazolidin-2-one **16** was deacetylated with ammonia in methanol to give derivative **17** in a 79% yield after chromatographic purification (Scheme 3).

2.1. X-ray structural analysis

An ORTEP[42] view of **16** showing the atomic labelling scheme is shown in Figure 3. The typical asymmetry of the endocyclic bonds for the pyranose ring [O-5–C-5=1.442(4) and O-5–C-1=1.388(4) Å], caused by the anomeric effect, is observed.[43] The geometry of the pyranose ring agrees with an almost undistorted $^4C_1$ chair conformation, in accordance with ^{1}H NMR data in solution, with the C-4 atom on one side [0.209(3) Å] and the C-1 atom on the other side [0.107(2) Å] of the least-squares best plane. In terms of

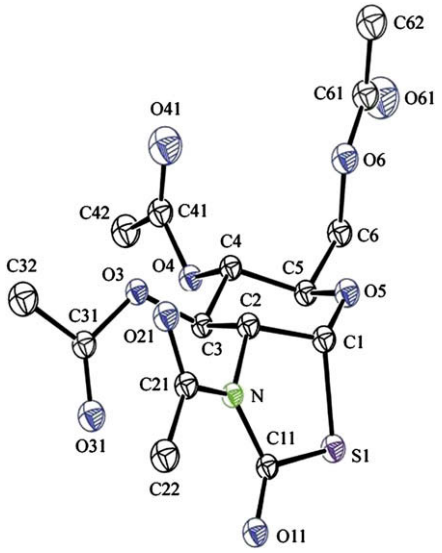


Figure 3. An ORTEP view of **16**.

ring-puckering coordinates,[44] amplitude and phase magnitudes are Q=0.506(3) Å, ϕ=4(1)° and θ=168.5(3)° for the sequence C-1–C-2–C-3–C-4–O-5. Nardelli[45] asymmetry parameters are ΔC_2(C-1)=0.225(1) and ΔC_s(O-5–C-1)=0.283(1). The geometry observed for the thiazole ring is intermediate between envelope and twist and the ring-puckering coordinates are Q=0.400(3) Å and ϕ=134 (4) for the sequence S-1–C-11–N–C-2–C-1. The asymmetry parameter is ΔC_2(C1)=0.212(1). The dihedral angle between the pyranose and the thiazolidine rings is 66.9(1)°. The chain C-6–O-6–C-61(O-61)–C-62 is planar (max. dev. 0.02 Å) and the conformation through the C-5–C-6 bond is *gauche–gauche* (*gg*), the major conformation found for glucopyranosyl derivatives in solid state.[46,47] The *N*-acetyl group is in the *s-trans* conformation (Fig. 2), in accordance with the conformation deduced in solution by NMR for **14** and **16**.

Isothiocyanation reaction was also carried out on D-mannosamine hydrochloride **18** (Scheme 4), using the same reaction conditions as described previously, to give cis-fused bicyclic thiocarbamate **20** in a 41% yield after column chromatography. This compound is the result of a spontaneous annelation through the non-detected isothiocyanate **19** and the hydroxyl group on C-3. It is remarkable that the cis-fused regioisomer **22** was not detected, probably due to the fact that for **19** the major isomer is expected to be the α-anomer,[48] together with the less nucleophilicity exhibited by anomeric hydroxyl groups. The instability of the trans-fused bicyclic thiocarbamate **21**, with the pyranose ring in the inverted form, precludes its formation. Vicinal coupling constants of the α-anomer of **20** ($J_{1,2}$ 0.0 Hz, $J_{2,3}$ 7.6 Hz, $J_{3,4}$ 3.7 Hz and $J_{4,5}$ 9.1 Hz) agree with ring conformations that differ significantly from the chair and which approach the $^0H_5$ half-chair, as found for 2,3-*O* carbonate protected *manno*- and rhamnopyranose derivatives.[49]

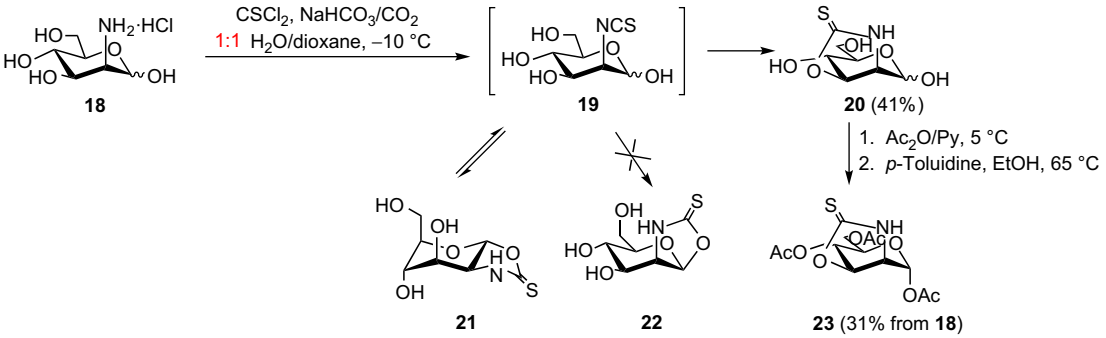
^{1}H NMR spectrum showed compound **20** (see Section 3) to be in an anomeric equilibrium, being the α-anomer the major isomer (5:1 in D_2O and 15:1 in DMSO-d_6); this is due to the anomeric effect and to the cancelation of the dipoles associated with the anomeric hydroxyl group and the thiocarbamate moiety. Furthermore, ^{1}H NMR showed a strong deshielding of H-3 (δ 5.60 ppm), indicating that hydroxyl group on C-3 is the one, which takes part in the annelation to form the thiocarbamate moiety.

Acetylation of the crude reaction of **20**, followed by selective N-deacetylation with *p*-toluidine in EtOH at 65 °C afforded the bicyclic derivative **23**, in a 31% overall yield for the three steps, after chromatographic purification. If the N-deacetylation step with ethanol is suppressed, a mixture of **23** and its *N*-acetylated derivative is detected. ^{1}H NMR spectrum showed compound **23** to be the α-anomer, whereas the β-anomer was not isolated from the reaction mixture.

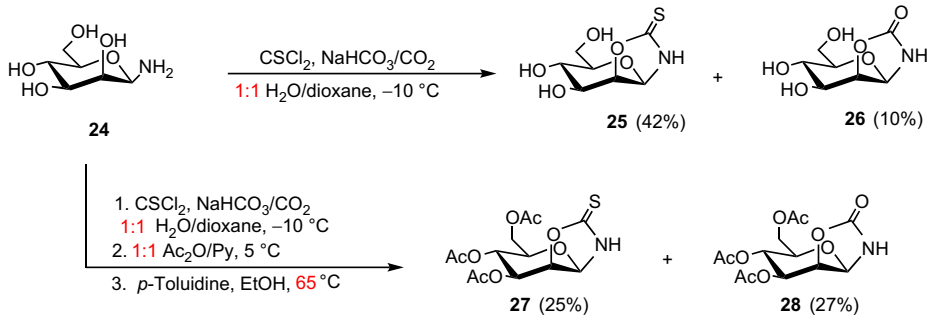
The same isothiocyanation reaction conditions as described for D-glucosamine and D-mannosamine were used when starting from β-D-mannopyranosylamine **24** (Scheme 5), obtained by saturating a suspension of D-mannose in methanol with ammonia.[50] In this case, treatment with thiophosgene affords cis-fused bicyclic thiocarbamate **25** as the major product (42% yield after column chromatography). This compound is obtained as a result of a spontaneous annelation of the non-detected isothiocyanate derivative with the axial hydroxyl group on C-2. Together with thiocarbamate **25**, carbamate **26**[19b] was unexpectedly obtained in a 10% yield; the formation of this compound might be explained considering thiophosgene-mediated oxidation of thiocarbamate **25** under the reaction conditions, although these carbamates were not detected together with thiocarbamates **11** and **20**, prepared from glucosamine and mannosamine, respectively. The oxidation of thioureas and thioamides into the corresponding oxo derivatives by using thiosphosgene has been reported.[51]

^{1}H and ^{13}C NMR spectra of **25** and **26** showed that in solution these compounds are not in equilibrium with the corresponding glycosyl isothiocyanates or isocyanates. Reaction of compound **25** with *p*-toluidine did not afford the corresponding mannopyranosyl thiourea, which again confirms that cis-fused bicyclic thiocarbamates do not act as latent isothiocyanates in the reaction with nucleophiles.

Conventional acetylation of the crude reaction mixture of **25** and **26**, followed by heating in EtOH in the presence of *p*-toluidine afforded the *N*-deacetylated derivatives **27** and **28**,[19b] with an overall yield for the three steps (isothiocyanation, acetylation and



Scheme 4.



Scheme 5.

N-deacetylation) of 25 and 27%, respectively, after preparative TLC purification. The coupling constants $J_{1,2}$ for **25**–**28** exhibit an unusual large value (3.2–4.0 Hz) for a β-anomer derived from mannosamine **24** in the $^4C_1$ conformation. The full set of vicinal coupling constants suggests that the sugar ring of **25**–**28** should adopt a preferential $^1S_5$ conformation in solution, a conformation found for mannosyl residues during enzymatic hydrolysis.[52]

In conclusion, the isothiocyanation reactions of 1,2-*cis*-configured glycosylamines and amino sugars with thiophosgene afforded cis-fused bicyclic thiocarbamates (glycopyrano-1,3-oxazolidine-2-thiones). Treatment of these compounds with aromatic amines did not afford thioureas unlike their isomeric trans-counterparts, showing that the cis-fused hydrindane-type bicycles are more stable due to a lower ring strain. An unprecedented isomerization of a *N*-acetyl glucopyrano-1,3-oxazolidine-2-thione into a glucopyrano-1,3-thiazolidin-2-one was also reported, and its structure confirmed with X-ray crystallography.

3. Experimental

3.1. General procedures

Melting points were recorded on an Electrothermal apparatus and are uncorrected, optical rotations were measured with a Perkin–Elmer 241 polarimeter, and IR spectra (KBr disks) were obtained with an FTIR Bomem MB-120 spectrophotometer. ^{1}H (300 and 500 MHz) and ^{13}C (75.5 and 125.7 MHz) NMR spectra were recorded on Bruker AMX-300 and AMX-500 spectrometers. The assignments of ^{1}H and ^{13}C signals were confirmed by homonuclear COSY and heteronuclear 2D correlated spectra, respectively. Mass spectra were recorded on Kratos MS-80-RFA and Micromass AutoSpeQ mass spectrometers. TLC was performed on aluminium pre-coated sheets (E. Merck Silica Gel F_{254}); spots were visualized by UV light, by charring with 10% H_2SO_4 in EtOH. Column chromatography was performed using E. Merck Silica Gel 60 (40–63 mm). Microanalysis was performed at the 'Instituto de Investigaciones Químicas', Seville, Spain.

3.2. (1,2-Dideoxy-α-D-glucopyranoso)[2,1-*d*]oxazolidine-2-thione (11)

To a suspension of 2-amino-2-deoxy-D-glucosamine hydrochloride (200 mg, 0.93 mmol) and $NaHCO_3$ (312 mg, 3.71 mmol) in 1:1 water–dioxane (4 mL) saturated with CO_2 (pH 8), was added thiophosgene (0.08 mL, 1.14 mmol, 1.2 equiv). The mixture was stirred at −10 °C for 30 min and then it was concentrated to dryness. The residue was purified by column chromatography (5:1 CH_2Cl_2–MeOH) to give **11** as a syrup: 159 mg, 77%. R_f 0.42 (5:1 CH_2Cl_2–MeOH); IR: ν_{max} 3195 (OH, NH), 1636, 1526 (NHC=S) cm^{-1}; ^{1}H NMR (300 MHz, CD_3OD) δ 6.11 (d, 1H, $J_{1,2}$=6.8 Hz, H-1), 3.87 (dd, 1H, $J_{2,1}$=6.8 Hz, $J_{2,3}$=5.2 Hz, H-2), 3.79 (dd, 1H, $J_{6a,5}$=2.1 Hz, $J_{6a,6b}$=12.2 Hz, H-6a), 3.67 (dd, 1H, $J_{6b,5}$=4.7 Hz, $J_{6b,6a}$=12.2 Hz, H-6b), 3.64 (t, 1H, $J_{3,2}$=5.2 Hz, $J_{3,4}$=5.3 Hz, H-3), 3.51 (ddd, 1H, $J_{5,4}$=9.1 Hz, $J_{5,6a}$=2.1 Hz, $J_{5,6b}$=4.7 Hz, H-5), 3.50 (t, 1H, $J_{4,3}$=5.3 Hz, $J_{4,5}$=9.1 Hz, H-4); ^{13}C NMR (75.5 MHz, CD_3OD) δ 190.0 (CS), 104.3 (C-1), 76.3 (C-5), 74.8 (C-3), 69.2 (C-4), 62.6 (C-6), 59.9 (C-2); FABMS *m*/*z* 222 ([M+H]$^+$, 100%), 443 ([2M+H]$^+$, 12%). HRCI-MS *m*/*z* calcd for $C_7H_{12}NO_5S$ [M+H]$^+$: 222.0436, found: 222.0432.

3.3. *N*-Acetyl-(3,4,6-tri-*O*-acetyl-1,2-dideoxy-α-D-glucopyranoso)[2,1-*d*]oxazolidine-2-thione (14)

To a suspension of 2-amino-2-deoxy-D-glucosamine hydrochloride (1.0 g, 4.64 mmol) and $NaHCO_3$ (1.29 g, 15.32 mmol) in 1:1 water–dioxane (20 mL) saturated with CO_2 (pH 8) was added thiophosgene (0.42 mL, 5.48 mmol). The mixture was stirred at −10 °C for 30 min and then it was concentrated to dryness. The residue was conventionally acetylated with an 1:1 Ac_2O–Py mixture (16 mL) and crystallized from EtOH to give **14**: 0.81 g, 45%; mp 109–111 °C; R_f 0.68 (Et_2O); $[\alpha]_D^{25}$ −34 (*c* 1.0, CH_2Cl_2); IR: ν_{max} 1750 (C=O), 1231 (AcO) cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.10 (d, 1H, $J_{1,2}$=7.0 Hz, H-1), 5.37 (dd, 1H, $J_{3,2}$=4.5 Hz, $J_{3,4}$=6.0 Hz, H-3), 5.08 (m, 1H, $J_{4,2}$=0.8 Hz, $J_{4,5}$=7.5 Hz, H-4), 4.79 (m, 1H, H-2), 4.35 (dd, 1H, $J_{6a,5}$=5.5 Hz, $J_{6a,6b}$=12.3 Hz, H-6a), 4.25 (dd, 1H, $J_{6b,5}$=3.0 Hz, $J_{6b,6a}$=12.3 Hz, H-6b), 4.10 (ddd, 1H, $J_{5,4}$=7.5 Hz, $J_{5,6a}$=5.5 Hz, $J_{5,6b}$=3.0 Hz, H-5), 2.79 (s, 3H, NAc), 2.11, 2.10, 2.06 (3s, 3H each, 3×OAc); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 183.2 (CS), 170.7, 170.3, 169.2, 168.9 (4$COCH_3$), 99.4 (C-1), 70.4 (C-5), 68.1 (C-3), 65.4 (C-4), 62.3 (C-6), 56.9 (C-2), 26.3 (NCOCH_3), 20.6, 20.5, 20.4 (3C, 3×$COCH_3$); FABMS *m*/*z* 390 ([M+H]$^+$, 100%). Anal. Calcd for $C_{15}H_{19}NO_9S$: C, 46.27; H, 4.92; N, 3.60. Found: C, 46.24; H, 4.81; N, 3.70.

3.4. (3,4,6-Tri-*O*-acetyl-1,2-dideoxy-α-D-glucopyranoso)[2,1-*d*]oxazolidine-2-thione (15)

Method A: to a solution of **14** (50 mg, 0.13 mmol) in EtOH (7 mL) was added *p*-toluidine (28 mg, 0.26 mmol). The solution was heated at 65 °C for 13 h and then it was concentrated to dryness and the residue was purified by preparative TLC (80:1 CH_2Cl_2–MeOH, two elutions) to give **15** as a syrup (35 mg, 78%). Method B: to a solution of **14** (100 mg, 0.26 mmol) in EtOH (7 mL) was added Silica Gel 60 (40–60 mesh, 400 mg) and the mixture was refluxed for 48 h. Filtration and purification of the residue by preparative TLC (80:1 CH_2Cl_2–MeOH) afforded **15** as a syrup: 43 mg, 48%; R_f 0.17 (80:1 CH_2Cl_2–MeOH); $[\alpha]_D^{25}$ +47 (*c* 0.6, CH_2Cl_2); IR: ν_{max} 3302 (NH), 1746 (C=O), 1508 (NHC=S), 1229 (AcO) cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28 (s, 1H, NH), 6.21 (d, 1H, $J_{1,2}$=7.3 Hz, H-1), 5.09 (dd, 1H, $J_{4,3}$=5.9 Hz, $J_{4,5}$=9.1 Hz, H-4), 4.91 (dd, 1H, $J_{3,2}$=3.9 Hz, $J_{3,4}$=5.9 Hz, H-3), 4.36 (dd, 1H, $J_{6a,5}$=5.0 Hz, $J_{6a,6b}$=12.4 Hz, H-6a), 4.21 (dd, 1H, $J_{6b,5}$=2.6 Hz, $J_{6b,6a}$=12.4 Hz, H-6b), 4.07 (ddd, 1H, $J_{5,4}$=9.1 Hz,

$J_{5,6a}$=5.0 Hz, $J_{5,6b}$=2.6 Hz, H-5), 4.02 (dd, 1H, $J_{2,1}$=7.3 Hz, $J_{2,3}$=3.9 Hz, H-2), 2.13, 2.10, 2.10 (3s, 3H each, 3×OAc); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 187.7 (CS), 170.5, 170.4, 170.0 (3$COCH_3$), 101.4 (C-1), 73.5 (C-3), 69.1 (C-5), 65.5 (C-4), 61.8 (C-6), 56.8 (C-2), 20.6, 20.6, 20.5 (3$COCH_3$); FABMS m/z 370 ([M+Na]$^+$, 100%), 348 ([M+H]$^+$, 24%). Anal. Calcd for $C_{13}H_{17}NO_8S$: C, 44.95; H, 4.93; N, 4.03. Found: C, 44.81; H, 4.84; N, 3.99.

3.5. *N*-Acetyl-(3,4,6-tri-*O*-acetyl-1,2-dideoxy-α-D-glucopyranoso)[2,1-*d*]thiazolidin-2-one (16)

To a solution of **14** (151 mg, 0.39 mmol) in DMF (9 mL) was added KSCN (76 mg, 0.78 mmol, 2.0 equiv) and the solution was heated at 125 °C for 5.5 h. Then it was concentrated to dryness, diluted with CH_2Cl_2 (15 mL) and washed with water (2×10 mL). The organic layer was dried over $MgSO_4$, filtered and concentrated to dryness. The residue was purified by preparative TLC (80:1 CH_2Cl_2–MeOH, two elutions) to afford **16**: 78 mg, 52%. R_f 0.68 (Et_2O); $[\alpha]_D^{25}$ −117 (*c* 1.2, CH_2Cl_2); mp: 107–108 °C (Et_2O); IR ν_{max} 1746 (C=O), 1713 (S–C=O), 1235 (AcO) cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.21 (d, 1H, $J_{1,2}$=6.7 Hz, H-1), 5.49 (m, 1H, $J_{3,2}$=8.2 Hz, $J_{3,4}$=9.4 Hz, $J_{3,5}$=0.7 Hz, H-3), 5.19 (t, 1H, $J_{4,3}$=9.4 Hz, $J_{4,5}$=9.5 Hz, H-4), 5.04 (dd, 1H, $J_{2,1}$=6.7 Hz, $J_{2,3}$=8.2 Hz, H-2), 4.35 (dd, 1H, $J_{6a,5}$=4.6 Hz, $J_{6a,6b}$=12.4 Hz, H-6a), 4.24 (m, 1H, H-5), 4.13 (dd, 1H, $J_{6b,5}$=2.1 Hz, $J_{6b,6a}$=12.4 Hz, H-6b), 2.41 (s, 3H, NAc), 2.09, 2.05, 2.00 (3s, 3H each, 3×OAc); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 170.4 (×2), 169.3, 169.0, 168.3 (5CO), 80.4 (C-1), 72.1 (C-3), 70.4 (C-5), 66.0 (C-4), 61.3 (C-6), 59.4 (C-2), 25.3 (NAc), 20.6, 20.6, 20.4 (3×OAc). EIMS m/z 389 ([M]$^+$, 6%). Anal. Calcd for: $C_{15}H_{19}NO_9S$; C, 46.27%; H, 4.92%; N, 3.60%; S, 8.24%. Found: C, 46.53%; H, 5.03%; N, 3.60%; S, 8.37%.

3.6. (1,2-Dideoxy-α-D-glucopyranoso)[2,1-*d*]thiazolidin-2-one (17)

Through a solution of **16** (138 mg, 0.280 mmol) in dry methanol (4 mL) at −10 °C was bubbled ammonia for 15 min and then the solution was kept at 5 °C for 1.5 h. Then it was concentrated to dryness and purified by preparative TLC (4:1 CH_2Cl_2–MeOH) to give **17** as a white solid: 62 mg, 79%. R_f 0.29 (5:1 CH_2Cl_2–MeOH); $[\alpha]_D^{27}$ +31 (*c* 0.8, H_2O); IR ν_{max} 3281 (OH), 1667 (S–C=O) cm^{-1}; ^{1}H NMR (300 MHz, D_2O) δ 6.37 (m, 1H, $J_{1,2}$=6.7 Hz, H-1), 3.89–3.81 (m, 3H, H-2, H-3, H-4), 3.84 (dd, 1H, $J_{6a,5}$=2.3 Hz, $J_{6a,6b}$=12.7 Hz, H-6a), 3.73 (dd, 1H, $J_{6b,5}$=6.4 Hz, $J_{6b,6a}$=12.7 Hz, H-6b), 3.50 (ddd, 1H, $J_{4,5}$=9.2 Hz, $J_{5,6a}$=2.3 Hz, $J_{5,6b}$=6.4 Hz, H-5); ^{13}C NMR (75.5 MHz, D_2O) δ 176.9 (CO), 85.2 (C-1), 75.9, 75.0 (C-3, C-4), 69.2 (C-5), 61.9 (C-6), 61.1 (C-2); CIMS m/z 222 ([M+H]$^+$, 100%); HRCI-MS calcd for $C_7H_{12}NO_5S$ [M+H]$^+$: 222.0436. Found: 222.0435. Anal. Calcd for: $C_7H_{11}NO_5S$: C, 38.00; H, 5.01; N, 6.33. Found: C, 38.04; H, 5.08; N, 6.36.

3.7. (2,3-Dideoxy-D-mannopyranoso)[2,3-*d*]oxazolidine-2-thione (20)

To a suspension of D-mannosamine hydrochloride (200 mg, 0.93 mmol) and $NaHCO_3$ (312 mg, 3.71 mmol) in 1:1 water–dioxane (4 mL) at −10 °C was added thiophosgene (0.10 mL, 1.39 mmol). The mixture was stirred at that temperature for 35 min and then it was concentrated to dryness. The residue was dissolved in water (5 mL) and washed with CH_2Cl_2 (3×5 mL). The organic layer was concentrated to dryness and treated with EtOH. After removal of the salts the residue was purified by column chromatography (CH_2Cl_2 → 5:1 CH_2Cl_2–MeOH) to give **20** as a syrup: 84 mg, 41%. *Rf* 0.58 (5:1 CH_2Cl_2–MeOH); $[\alpha]_D^{25}$ +56 (*c* 0.6, H_2O); IR ν_{max} 3370 (OH, NH), 1551 (NHC=S) cm^{-1}; ^{1}H NMR (300 MHz, D_2O) δ 5.60 (dd, 1H, $J_{3,2}$=7.4 Hz, $J_{3,4}$=3.7 Hz, H-3, **20α**), 5.46 (dd, 1H, $J_{3,2}$=7.6 Hz, $J_{3,4}$=2.4 Hz, H-3, **20β**), 5.38 (s, 1H, $J_{1,2}\approx$0.0 Hz, H-1, **20α**), 5.27 (d, 1H, $J_{1,2}$=3.6 Hz, H-1, **20β**), 4.54 (dd, 1H, $J_{2,1}$=3.6 Hz, $J_{2,3}$=7.6 Hz, H-2, **20β**), 4.50 (d, 1H, $J_{2,1}\approx$0.0 Hz, $J_{2,3}$=7.4 Hz, H-2, **20α**), 4.27 (dd, 1H, $J_{4,3}$=3.7 Hz, $J_{4,5}$=9.1 Hz, H-4, **20α**), 3.88 (ddd, 1H, $J_{5,4}$=9.1 Hz, $J_{5,6a}$=2.8 Hz, $J_{5,6b}$=5.5 Hz, H-5, **20α**), 3.78 (dd, 1H, $J_{6a,5}$=2.8 Hz, $J_{6a,6b}$=12.2 Hz, H-6a, **20α**), 3.63 (dd, 1H, $J_{6b,5}$=5.5 Hz, $J_{6b,6a}$=12.2 Hz, H-6b, **20α**); ^{13}C NMR (75.5 MHz, D_2O) for **20α** δ 191.0 (CS), 102.7 (C-1), 89.0 (C-3), 81.4 (C-4), 70.9 (C-5), 69.1 (C-2), 65.4 (C-6); CIMS m/z 204 ([M+H−H_2O]$^+$, 48%), 222 ([M+H]$^+$, 100%); HRCIMS m/z calcd for $C_7H_{12}NO_5S$ [M+H]$^+$: 222.0436, found: 222.0446.

3.8. (1,4,6-Tri-*O*-acetyl-2,3-dideoxy-α-D-mannopyranoso)[2,3-*d*]oxazolidine-2-thione (23)

To a suspension of D-mannosamine hydrochloride (150 mg, 0.70 mmol) and $NaHCO_3$ (234 mg, 2.78 mmol) in 1:1 water–dioxane (2 mL) at −10 °C was added thiophosgene (0.079 mL, 1.04 mmol). The mixture was stirred at that temperature for 35 min and then it was concentrated to dryness and the residue was acetylated with 1:1 Ac_2O–Py (6 mL) at 5 °C for 24 h. After conventional work-up, the residue was dissolved in EtOH (3 mL) and to the solution was added *p*-toluidine (150 mg, 1.40 mmol). The resulting solution was heated at 65 °C for 2 h and purified with preparative TLC (3:1 EtOAc–hexane and afterwards Et_2O) to give **23** as a syrup: 74 mg, 31%. *Rf* 0.43 (80:1 CH_2Cl_2–MeOH); $[\alpha]_D^{24}$ −10 (*c* 1.9, CH_2Cl_2); IR ν_{max} 3333 (NH), 1746 (C=O), 1516 (NHC=S), 1221 (AcO) cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.16 (br s, 1H, NH), 6.17 (s, 1H, $J_{1,2}\approx$0.0 Hz, H-1), 5.47 (dd, 1H, $J_{3,2}$=7.5 Hz, $J_{3,4}$=3.9 Hz, H-3), 5.27 (ddd, 1H, $J_{5,4}$=8.1 Hz, $J_{5,6a}$=2.7 Hz, $J_{5,6b}$=4.8 Hz, H-5), 4.56 (dd, 1H, $J_{6a,5}$=2.7 Hz, $J_{6a,6b}$=12.3 Hz, H-6a), 4.52 (d, 1H, $J_{2,1}\approx$0.0 Hz, $J_{2,3}$=7.5 Hz, H-2), 4.43 (dd, $J_{4,3}$=3.9 Hz, $J_{4,5}$=8.1 Hz 1H, H-4), 4.17 (dd, 1H, $J_{6b,5}$=4.8 Hz, $J_{6b,6a}$=12.3 Hz, H-6b), 2.09 (×2), 2.06 (3s, 3H each, 3×OAc); ^{13}C NMR (300 MHz, $CDCl_3$) δ 188.8 (CS), 170.6, 169.5, 169.3 (3CO), 99.8 (C-1), 84.9 (C-3), 80.2 (C-4), 68.3 (C-5), 66.0 (C-2), 62.2 (C-6), 20.8, 20.7, 20.6 (3×OAc); CIMS m/z 288 ([M+H−AcOH]$^+$, 100%), 306 ([M+H−CH_2CO]$^+$, 47%), 348 ([M+H]$^+$, 48%); HRCI-MS calcd for $C_{13}H_{18}NO_8S$ [M+H]$^+$ 348.0753; found: 348.0746.

3.9. (1,2-Dideoxy-β-D-mannopyranoso)[1,2-*d*]oxazolidine-2-thione (25) and (1,2-dideoxy-β-D-mannopyranoso)[1,2-*d*]oxazolidin-2-one (26)

To a suspension of β-D-mannopyranosylamine monohydrate (200 mg, 1.01 mmol) and $NaHCO_3$ (278 mg, 3.31 mmol) in 1:1 water–dioxane (4 mL) at −10 °C was added thiophosgene (0.12 mL, 1.66 mmol). The mixture was stirred at that temperature for 30 min and then was concentrated to dryness. The residue was dissolved in water (5 mL) and washed with CH_2Cl_2 (2×5 mL). The aqueous layer was concentrated to dryness and treated with EtOH. After removal of the salts, the filtrate was purified by column chromatography (CH_2Cl_2 → 5:1 CH_2Cl_2–MeOH). Eluted first was **25** (103 mg, 42%); R_f 0.40 (5:1 CH_2Cl_2–MeOH); $[\alpha]_D^{26}$ −65 (*c* 0.8, H_2O); IR ν_{max} 3318 (OH, NH), 1491 (NHC=S) cm^{-1}; ^{1}H NMR (300 MHz, D_2O) δ 5.47 (d, 1H, $J_{1,2}$=3.7 Hz, H-1), 4.98 (dd, 1H, $J_{2,1}$=3.7 Hz, $J_{2,3}$=4.6 Hz, H-2), 4.02 (dd, 1H, $J_{3,2}$=4.6 Hz, $J_{3,4}$=9.5 Hz, H-3), 3.84 (dd, 1H, $J_{6a,5}$=2.5 Hz, $J_{6a,6b}$=12.3 Hz, H-6a), 3.66 (dd, 1H, $J_{6b,5}$=6.4 Hz, $J_{6b,6a}$=12.3 Hz, H-6b), 3.58 (t, 1H, $J_{4,3}$=9.5 Hz, $J_{4,5}$=9.5 Hz, H-4), 3.44 (ddd, 1H, $J_{5,4}$=9.5 Hz, $J_{5,6a}$=2.5 Hz, $J_{5,6b}$=6.4 Hz, H-5); ^{13}C NMR (75.5 MHz, D_2O) δ 192.7 (CS), 85.8 (C-2), 84.0 (C-1), 76.8 (C-5), 71.0 (C-3), 68.1 (C-4), 62.0 (C-6); CIMS m/z 222 ([M+H]$^+$, 27%); HRCI-MS m/z calcd for $C_7H_{12}NO_5S$ [M+H]$^+$ 222.0436, found: 222.0425.

Eluted second was **26** (33 mg, 10%); R_f=0.19 (5:1 CH_2Cl_2–MeOH); $[\alpha]_D^{26}$ −31 (*c* 0.6, H_2O); IR ν_{max} 3401 (OH, NH), 1750, 1647 (NHC=O) cm^{-1}; ^{1}H NMR (300 MHz, D_2O) δ 5.36 (d, 1H, $J_{1,2}$=3.2 Hz, H-1), 4.82 (dd, 1H, $J_{2,1}$=3.2 Hz, $J_{2,3}$=4.6 Hz, H-2), 3.98 (dd, 1H, $J_{3,2}$=4.6 Hz, $J_{3,4}$=9.6 Hz, H-3), 3.88 (dd, 1H, $J_{6a,5}$=2.4 Hz,

$J_{6a,6b}$=12.2 Hz, H-6a), 3.70 (dd, 1H, $J_{6b,5}$=6.4 Hz, $J_{6b,6a}$=12.2 Hz, H-6b), 3.62 (t, 1H, $J_{4,3}$=9.6 Hz, $J_{4,5}$=9.6 Hz, H-4), 3.44 (ddd, 1H, $J_{5,4}$=9.6 Hz, $J_{5,6a}$=2.4 Hz, $J_{5,6b}$=6.4 Hz, H-5); ^{13}C NMR (125.7 MHz, D_2O) δ 162.0 (CO), 82.3 (C-1), 80.6 (C-2), 76.4 (C-5), 71.6 (C-3), 68.2 (C-4), 62.0 (C-6); CIMS m/z 188 ([M+H−H_2O]$^+$, 12%), 206 ([M+H]$^+$, 20%); HRCI-MS m/z calcd for $C_7H_{12}NO_6$ [M+H]$^+$ 206.0664, found: 206.0667.

3.10. (3,4,6-Tri-*O*-acetyl-1,2-dideoxy-β-D-mannopyranoso)[1,2-*d*]oxazolidine-2-thione (27) and (3,4,6-tri-*O*-acetyl-1,2-dideoxy-β-D-mannopyranoso)[1,2-*d*]oxazolidin-2-one (28)

To a suspension of β-D-mannopyranosylamine monohydrate (600 mg, 3.04 mmol) and $NaHCO_3$ (847 mg, 10.08 mmol) in 1:1 water–dioxane (12 mL) at −10 °C was added thiophosgene (0.39 mL, 5.04 mmol). The mixture was stirred at that temperature for 30 min and then it was concentrated to dryness and the residue was acetylated with 1:1 Ac_2O–Py (20 mL) at 5 °C for 24 h. After conventional work-up, the residue was dissolved in EtOH (20 mL) and to the solution was added *p*-toluidine (652 mg, 6.08 mmol). The resulting solution was heated at 65 °C for 5 h and purified with preparative TLC (40:1 CH_2Cl_2–MeOH). Eluted first was **27** (260 mg, 25%); R_f=0.23 (80:1 CH_2Cl_2–MeOH); $[\alpha]_D^{26}$ −106 (*c* 1.2, CH_2Cl_2); IR ν_{max} 3306 (NH), 1746 (C=O), 1487 (NHC=S), 1229 (AcO) cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.16 (s, 1H, NH), 5.39 (d, 1H, $J_{1,2}$=4.0 Hz, H-1), 5.33 (dd, 1H, $J_{3,2}$=4.0 Hz, $J_{3,4}$=9.5 Hz, H-3), 5.23 (dd, 1H, $J_{4,3}$=9.5 Hz, $J_{4,5}$=8.2 Hz, H-4), 5.05 (t, 1H, $J_{2,1}$=4.0 Hz, $J_{2,3}$=4.0 Hz, H-2), 4.24 (dd, 1H, $J_{6a,5}$=2.8 Hz, $J_{6a,6b}$=12.4 Hz, H-6a), 4.14 (dd, 1H, $J_{6b,5}$=6.0 Hz, $J_{6b,6a}$=12.4 Hz, H-6b), 3.76 (ddd, 1H, $J_{5,4}$=8.2 Hz, $J_{5,6a}$=2.8 Hz, $J_{5,6b}$=6.0 Hz, H-5), 2.13, 2.07, 2.06 (3s, 3H each, 3×OAc); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ 190.2 (CS), 170.7, 170.2, 169.1 (3CO), 82.6 (C-1), 80.2 (C-2), 72.4 (C-5), 68.7 (C-3), 65.4 (C-4), 62.1 (C-6), 20.6, 20.5, 20.4 (3×OAc); CIMS m/z 348 ([M+H]$^+$, 100%); HRCI-MS calcd for $C_{13}H_{18}NO_8S$ [M+H]$^+$ 348.0753; found: 348.0766.

Eluted second was **28** (269 mg, 27%); R_f 0.10 (80:1 CH_2Cl_2–MeOH); $[\alpha]_D^{25}$ −60 (*c* 0.9, CH_2Cl_2); IR ν_{max} 3275 (NH), 1755, 1740 (C=O), 1246, 1223 (AcO) cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.18 (s, 1H, NH), 5.26 (t, 1H, $J_{4,3}$=9.6 Hz, $J_{4,5}$=9.6 Hz, H-4), 5.21 (d, 1H, $J_{1,2}$=3.9 Hz, H-1), 5.20 (dd, 1H, $J_{3,2}$=4.5 Hz, $J_{3,4}$=9.6 Hz, H-3), 4.84 (t, 1H, $J_{2,1}$=3.9 Hz, $J_{2,3}$=4.5 Hz, H-2), 4.24 (dd, 1H, $J_{6a,5}$=5.4 Hz, $J_{6a,6b}$=12.3 Hz, H-6a), 4.14 (dd, 1H, $J_{6b,5}$=2.7 Hz, $J_{6b,6a}$=12.3 Hz, H-6b), 3.70 (ddd, 1H, $J_{5,4}$=9.6 Hz, $J_{5,6a}$=5.4 Hz, $J_{5,6b}$=2.7 Hz, H-5), 2.12, 2.08, 2.06 (3s, 3H each, 3×OAc); ^{13}C NMR (300 MHz, $CDCl_3$) δ 170.5, 170.1, 169.1, 157.3 (4CO), 80.8 (C-1), 74.9 (C-2), 71.9 (C-5), 69.4 (C-3), 65.4 (C-4), 62.1 (C-6), 20.6, 20.4 (3×OAc); CIMS m/z 272 ([M+H−AcOH]$^+$, 100%), 290 ([M+H−CH_2CO]$^+$, 64%), 332 ([M+H]$^+$, 94%), 543 ([2M+H−2AcOH]$^+$, 6%), 621 ([2M+H−CH_2CO]$^+$, 10%), 663 ([2M+H]$^+$, 16%); HRCI-MS calcd for $C_{13}H_{18}NO_9$ [M+H]$^+$ 332.0982, found: 332.0977.

3.11. Experimental conditions for the crystal structure determination of 16

Crystals of compound **16** with molecular formula $C_{15}H_{19}NO_9S$ appear as colourless prisms with well shaped faces. Crystal size, 0.16×0.20×0.40 mm; crystal system, monoclinic; space group $P2_1$; unit-cell dimensions, a=10.797(2), b=8.290(3), c=11.116(2) Å, β=109.433(9)°; unit-cell volume, V-=938.3(4) Å^3; formula units per unit cell, Z=2; calculated density, D_x=1.378 g cm^{-3}; measured density, D_m=1.38 g cm^{-3}; F(000) value, 408; absorption coefficient, μ=0.219 mm^{-1}; temperature, T=293 K. Unit-cell parameters and crystal orientation matrix were determined on a CAD-4 Enraf–Nonius automated four-circle diffractometer from the least-squares treatment of the setting angles of 25 independent reflections. Intensity data were collected at room temperature in the $\omega/2\theta$ scan mode, using Mo Kα radiation, (λ=0.071069 Å), θ_{max}=30°; range of h, k and l, −15<h<14, −11<k<11, 0<l<15. Three standard reflections were measured every hour to monitor crystal stability and were re-centred after every hundred measured reflections to monitor crystal orientation. No significant intensity changes were observed. Number of measured reflections, 5451; number of significant reflections, 3677; criterion for significance, $I>2\sigma(I_o)$; final R, 0.06; final $\omega R(F^2)$, 0.16; goodness-of-fit S, 0.99.

Corrections were made for Lorentz-polarization effects, but not for extinction and absorption. This effect was not taken into account because the crystal absorption with Mo radiation was practically negligible. The structure of **16** was solved by direct methods using SIR2002[53] to locate all non-hydrogen atoms. Refinement on F^2 was performed using SHELX97.[54] Atomic scattering factors were taken from International Tables for X-ray crystallography. The maximum and minimum residual densities in the final difference map were 0.26 and −0.21 e Å^{-3}, respectively. The geometrical analysis was performed using PARST.[55]

Crystallographic data for this structure have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 687037. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44 01223 336033 or e-mail: deposit@ccdc.cam.ac.uk].

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