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Heterocyclization of 3-deoxy-D-*erythro*-hexos-2-ulose-1,2-bis(thiosemicarbazone). Crystal structure of the major diastereomer

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Abstract

Both thiosemicarbazone groups of the derivative **1** of 3-deoxy-D-*erythro*-hexos-2-ulose underwent, on acetylation, a heterocyclization process to give (5*R*,5′*R*)-2,2′-diacetamido-4,4′-di-*N*-acetyl-5′-(1-deoxy-2,3,4-tri-*O*-acetyl-D-erythritol-1-yl)-5,5′-bis(1,3,4-thiadiazoline) (**2**) as a major product. The X-ray diffraction data of a single crystal of **2** indicated the *R*,*R* configuration for the stereocenters of the thiadiazoline rings (C-5 and C-5′). In the solid state, **2** adopts a sickle conformation (by clockwise rotation of the C-2–C-3 axis of the sugar chain) which has a S//O 1,3-parallel interaction. In solution, as determined by ^{1}H NMR spectroscopy which included NOE experiments, a similar sickle conformation was observed. From the reaction mixture of acetylation of **1** was isolated the bis(thiadiazoline) **3** as a by-product . The configuration of the C-5 and C-5′ stereocenters of **3** were respectively assigned as *S*,*R* by comparison of the physical and spectroscopic data of this compound with those of **2**.

Keywords: Sugar thiosemicarbazone; Thiadiazoline; Heterocyclization; X-ray diffraction

1. Introduction

Thiosemicarbazones and thiadiazolines display interesting biological properties, including antibacterial and tuberculostatic activities.[1,2] We have recently reported the synthesis of 2-(penta-*O*-acetylpentitol-1-yl)-1,3,4-thiadiazolines upon acetylation of the thiosemicarbazone derivatives of D-galactose, D-mannose, and D-glucose.[3] Diastereoisomers of the thiadiazoline having the D-galacto configuration for the alditol chain had been previously prepared by acetylation of penta-*O*-acetyl-*adehydo*-D-galactose thiosemicarbazone,[4] or directly by acetylation of free D-galactose thiosemicarbazone.[5] The acetylation of thiosemicarbazones derived from glyculoses having the carbonyl function located at different position of the carbohydrate molecule has been also described.[6–8] In some cases,[3–5] the preferential formation of one of the isomers from the two possible, depends on the configuration of the starting material and the acylating conditions, and it may be strongly influenced by steric hindrance,[6–8] as it was found for thiosemicarbazone derivatives of other natural chiral compounds.[9] However, the absolute configuration of the stereocenter of the thiadiazoline ring was not conclusively determined, although in some instances it has been assigned taking into account a proposed mechanistic pathway for the heterocyclization.[3,6] In this work we describe the formation of two 1,3,4-thiadiazolines rings in the same molecule, by acetylation of 3-deoxy-D-*erythro*-hexos-2-ulose-1,2-

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bis(thiosemicarbazone) (**1**). The configuration of the new stereocenters (C-5 and C-5′) in the heterocyclic moiety of the major diastereomer **2** was established by X-ray diffraction analysis of a single crystal. An isomeric bis(thiadiazoline) by-product **3** was isolated from the reaction mixture of acetylation. The stereochemistry of the new stereocenters of **3** was assigned by NMR techniques and by comparison of its properties with those of **2**.

2. Results and discussion

3-Deoxy-D-*erythro*-hexos-2-ulose-1,2-bis(thiosemicarbazone) (**1**) was readily prepared by the amine-promoted Amadori rearrangement of glucose to the corresponding 3-deoxyaldos-2-ulose, which was captured from the reaction mixture using thiosemicarbazide as a trapping agent.[10] Acetylation of **1** under standard conditions (acetic anhydride–pyridine) afforded a major product which crystallized from methanol.

Table 1
^{1}H NMR data for compounds **2** and **3**

	Compounds	
	2	**3**
Chemical shifts (δ, ppm)		
H-5	7.78	7.76
H-1a	3.87	2.81
H-1b	2.90	3.72
H-2	5.94	6.18
H-3	5.48	5.56
H-4a	4.49	4.48
H-4b	4.45	4.28
Coupling constants (J, Hz)		
$J_{1a,1b}$	16.3	16.1
$J_{1a,2}$	1.3	1.8
$J_{1b,2}$	8.2	9.9
$J_{2,3}$	2.2	3.7
$J_{3,4a}$	4.7	4.8
$J_{3,4b}$	6.9	6.6
$J_{4a,4b}$	12.0	12.1

Table 2
^{13}C NMR data for compounds **2** and **3**

Chemical shifts (δ, ppm)	Compounds	
	2	**3**
C-2	144.6	143.6
C-5	70.7	70.9
C-2′	149.1	149.2
C-5′	88.4	88.8
C-1	37.6	36.0
C-2	69.1	70.2
C-3	73.1	72.3
C-4	61.5	61.8

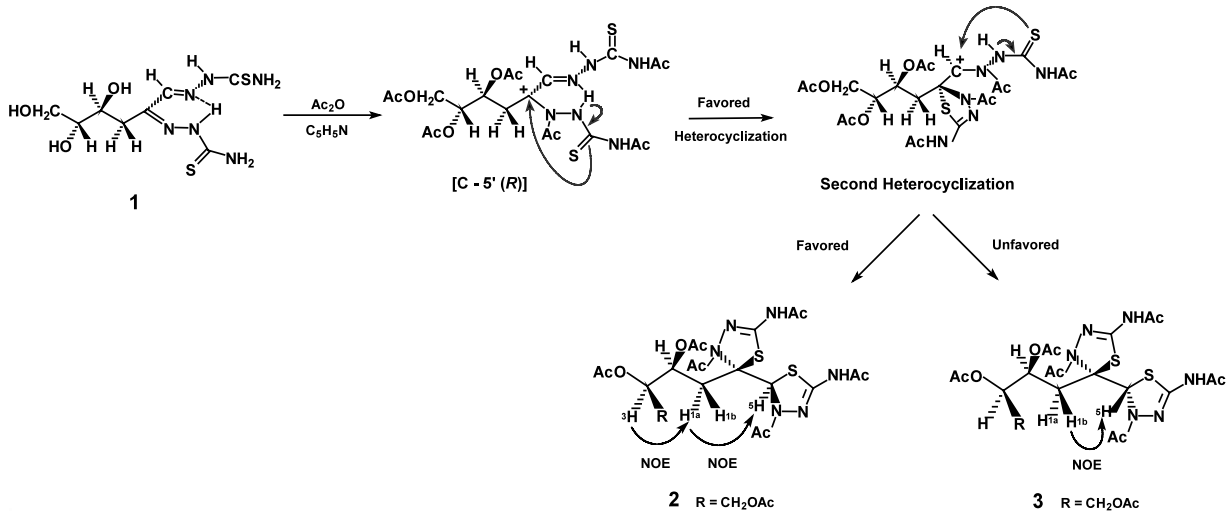
The ^{1}H NMR spectrum of this main product (Table 1) showed seven singlets (at ~ 2 ppm) as expected for the peracetylation of **1**. However, its ^{13}C NMR spectrum (Table 2) showed the absence of the thiocarbonyl carbon signals (expected at $\delta > 178$ ppm) and the resonances observed at higher fields (149.1, 144.6, 88.4, and 70.7) suggested the presence of two 1,3,4-thiadiazoline rings in the molecule.[3] Therefore, the structure of the product was tentatively assigned as **2** (Scheme 1), and then conclusively proved by X-ray crystallography.

Crystals of **2** suitable for X-ray diffraction analysis were obtained upon slow recrystallization of the product from aqueous methanol. Data collection information and details on the structure and refinement are described in Table 3. The selected atomic positions for the correct diastereomer are reported in Table 4, while the details of the molecular geometry are quoted in Table 5.

The schematic diagram of the structure of the bis(thiadiazoline) **2**, with the numbering scheme used,[†] is shown in Fig. 1. The X-ray analysis revealed that with the solvent employed (aqueous methanol) for growing the crystals a molecule of water is trapped during the crystallization. Therefore in the diagram, O-W1 and O-W2 represent the two disordered sites in which the hydration water molecule was trapped, displaying occupation factors of 65 and 35%, respectively. The former takes part in the hydrogen bonding, with the AcN–H group attached at C-2 acting as a proton donor and the oxygen of water as an acceptor, with a H···O length of 1.98 Å. The configuration of the new stereocenters C-5 and C-5′ (which corresponded respectively to C-1 and C-2 in the starting bis(thiosemicarbazone) **1**) of the 1,3,4-thiadiazoline rings was established as *R*,*R*, and hence compound **2** was identified as (5*R*,5′*R*)-2,2′-diacetamido-4,4′-di-*N*-acetyl-5′-(1-deoxy-2,3,4-tri-*O*-acetyl-D-*erythro*-tetritol-1-yl)-5,5′-bis(1,3,4-thiadiazoline).

In the solid state, compound **2** adopts a sickle conformation formed by a clockwise rotation of C-3 around the C-2–C-3 axis, by about 120°. Thus, the magnitude of the O-2–C-2–C-3–O-3 torsion angle of 63.0° is in contrast to the value expected for the planar

[†] For the purpose of convenience, double primed numbers (C-1″–C-4″) were used for atoms of the sugar chain attached to C-5′. However, in the text was employed the C-1–C-4 numbering for such atoms (and for the atoms bonded to them) in accordance with the terminology established for thiadiazoline derivatives.



Scheme 1.

zig–zag conformation (~ 180°). Similarly, a dihedral angle C-1–C-2–C-3–C-4 of 69.7° was measured. The extended conformation is found for the rest of the sugar chain; particularly, a slight distortion is observed along the C-5–C-5′ bond, with a small clockwise deviation (~ 13°) from ideality.

The ^{1}H NMR spectrum of **2** recorded in pyridine-d_5 admitted a first order analysis. The coupling constants values between H-1a and H-1b with H-2 (1.3 and 8.2 Hz) are in agreement with a respective gauche and anti orientation for such coupled protons. However, the small value for $J_{2,3}$ (2.2 Hz) in contrast to that expected for the extended conformation of **2**, points to a sickle, similar to that found in the solid state. As with compound **2**, a configurationally related *N*-(octyl)-D-gluconamide prefers also a sickle conformation formed by rotation of the (relatively) same linkage as in **2**.[14] It was assumed that such a rotation was induced by a 1,3-syn repulsion between oxygen substituents in the extended planar zig–zag conformation of the D-gluconamide derivative. The resulting rotamer should be stablized by an attractive gauche interaction between vicinal oxygen atoms (the attractive gauche effect).[15] The same S//O repulsion and the attractive gauche effect between oxygen atoms of the sugar chain are present in **2**. Furthermore, examples have been reported of molecular structures where linear conformations with avoidable 1,3-syn O//O or C//O interactions occur in solution[14,16] and in the solid state.[17]

Upon crystallization of **2** from the acetylation reaction mixture, monitoring of the methanolic mother liquors revealed the presence of other acylated products. Flash chromatography of this mixture afforded two main fractions. The less-polar fraction contained, along with **2**, another product (**3**) of very similar chromatographic mobility. However, compounds **2** and **3** could be separated by the selective solubility of **3** in acetone. Subsequent fractions from the column afforded a mixture of two other minor bis(thiadiazolines) diastereomers, which were not further analyzed.

The ^{1}H NMR spectra of **3** was subjected, as with **2**, to first-order analysis. Assignments of the signals in the ^{13}C NMR spectra **2** and **3** employed HETCOR experiments. When comparing the ^{1}H NMR spectrum of **2** with that of **3**, we found that the chemical shifts of the diastereotopic methylene protons (H-1a and H-1b) are inverted, as the signal having the larger $J_{1,2}$ value (this is, the proton H-1b anti oriented with respect to H-2) was more shielded in **2** than in **3**. The inversion in chemical shift was also observed for H-1a of both compounds. The shielding effect on H-1b in **2** may be attributed to the anisotropy induced by the heterocyclic group at C-5, which is facing such a proton. Therefore, the protection of H-1a in **3** suggests a 1,3-parallel interaction with the thiadiazoline ring at C-5, and hence the inversion of the configuration of this stereocenter in **3**. To confirm this hypothesis NOESY-phase sensitive experiments were conducted. Thus, as expected, cross-peaks between H-1a with H-5 and H-3 were observed for **2**. Also, in agreement with the structure proposed for **3**, H-1b showed a cross peak with H-5. These correlations confirmed the *S* configuration at C-5 for **3**. The C-5′configuration of **3** was tentatively assigned as *R*, taking into account the great resemblance of the spectra of **2** and **3**. Furthermore, the large magnitude for the optical rotation of **2** and **3**, and the fact that they are opposite in sign, agreed with the values determined for diasteromeric thiadiazolines derived from aldose thiosemicarbazones, which only differ in the configuration of the thiadiazoline ring stereocenter.[3,7,8]

The favored formation of the major isomers **2** and **3** by acylation of **1**, suggests the asymmetric induction of the sugar chain stereocenters during the heterocyclization. Preliminary theoretical calculations (MM +) on **1**

showed a less energetic structure (minimum difference of 4 kcal mol^{-1} with respect to other isomers) with an internal hydrogen bond, as that found in formazanes[18] and phenylosazones.[19] The cyclization reaction apparently starts by N-acylation of the C=N group, with development of a positive charge localized between the C and N atoms ($C{=}N^{+}Ac \leftrightarrow C^{+}{-}NAc$). Such an acetylation should occur initially on the nitrogen of the thiosemicarbazone group linked to C-2, as the other nitrogen electron pair is involved in hydrogen bonding

Table 3
Crystal data and structural determination and refinement data for **2**

Crystal data	
Molecular formula	$C_{22}H_{30}N_6O_{10}S_2{\cdot}H_2O$
Molecular weight	620.66
Crystal system	orthorhombic
Space group	$P2_12_12_1$ (no. 19)
Z	4
Cell dimensions (at 293 K)	
a (Å)	11.819(3)
b (Å)	13.845(3)
c (Å)	20.469(6)
V (Å^3)	3350(2)
M	620.66
D_{calcd} (g cm^{-3})	1.231
$F(000)$	1304
Structure determination and refinement data	
Crystal dimensions (mm)	$0.44 \times 0.28 \times 0.12$, colorless prisms
Number of reflections measured	3520 (29 rejected) (SIEMENS P4 diffractometer, $\omega/2\theta$ scan)
Number of unique reflections	3329
R_{int}	0.058, for 191 pairs
Number with $F^2/\sigma(F^2)>4$	1652 (50%)
Radiation: Mo K_α	($\lambda = 0.71073$ Å, graphite monochromator)
θ range (°)	1.78–25.00
Index range	$0 \le h \le 14$, $0 \le k \le 16$, $0 \le l \le 24$
Structure solution	
Direct methods plus difference Fourier (SHELX-97) [a]	Hydrogen atoms located at their expected positions and allowed to ride; those pertaining to the water molecule were not found
Structure refinement	
(SHELXL-97) [b]	Weighted [c] full-matrix least-squares on F^2, for the whole unique data set. Anisotropic displacement factors for non-H atoms; H atoms allowed to ride with isotropic displacement factors 1.2 times (1.5 for terminal methyl's) those of their hosts
Observation to parameter ratio	9.0
Final agreement factors	
S (goodness-of-fit on F^2: $[F^2>2\sigma(F^2)]$) [d]	0.985
$R_1(F)$ [e], $wR_2(F^2)$ [f] $[F^2>2\sigma(F^2)]$	0.064, 0.169
[All data]	0.155, 0.211
Flack's parameter for absolute configuration determination [g]	
Expected value for the correct [inverted] handedness	0.0 [1.0]
Refined value for the reported [inverted] structure	0.03(27)[0.73(27)]
Maximum peak, hole in final difference Fourier map (e Å^{-3})	0.27–0.25

[a] See Ref. 11.
[b] See Ref. 12.
[c] $w = 1/[\sigma^2(F_o^2)+(0.108P)^2]$, $P = (F_o^2+2F_c^2)/3$.
[d] $S = [\Sigma[w(F_o^2-F_c^2)^2]/(n-p)]]^{0.5}$, $n = 3329$, $p = 370$.
[e] $R_1 = \Sigma||F_o|-|F_c||/\Sigma|F_o|$.
[f] $wR_2 = [\Sigma[w(F_o^2-F_c^2)^2]/\Sigma[w(F_o^2)^2]]^{0.5}$.
[g] See Ref. 13.

Table 4
Atomic coordinates and equivalent isotropic displacement parameters (Å^2) for **2**

Atom [a]	x	y	z	U_{eq}
S-1	0.2176(2)	1.0362(2)	0.2603(1)	0.064(1)
S-1′	0.4538(2)	0.9438(2)	0.1809(1)	0.053(1)
O-2A	0.0727(8)	1.1466(7)	0.1976(5)	0.094(3)
O-2′B	0.5388(8)	0.9801(6)	0.0616(3)	0.102(3)
O-2″A	0.6699(6)	0.8262(5)	0.2412(3)	0.062(2)
O-2″A′	0.7860(7)	0.9472(7)	0.2110(4)	0.091(3)
O-3″B	0.8098(6)	0.8619(6)	0.3534(4)	0.066(2)
O-3″B′	0.7729(9)	1.0164(7)	0.3826(4)	0.093(3)
O-4A	0.2768(6)	0.7478(5)	0.3306(3)	0.065(2)
O-4′B	0.4154(7)	1.0343(6)	0.3925(3)	0.080(2)
O-4″C	0.7313(6)	0.6928(5)	0.4219(3)	0.069(2)
O-4″C′	0.5749(9)	0.7144(7)	0.4765(4)	0.113(3)
O-W1	0.0730(11)	0.8998(10)	0.0282(6)	0.099(6)
O-W2	0.893(2)	1.1821(19)	0.4694(12)	0.104(11)
N-2A	0.1041(8)	1.0043(8)	0.1443(5)	0.077(3)
N-2′B	0.5949(8)	1.0905(6)	0.1371(3)	0.064(3)
N-3	0.1925(7)	0.8758(7)	0.1924(4)	0.058(2)
N-4	0.2551(7)	0.8525(6)	0.2490(4)	0.062(2)
N-3′	0.5346(6)	1.0961(5)	0.2419(3)	0.048(2)
N-4′	0.4731(7)	1.0441(6)	0.2879(3)	0.054(2)
C-1″	0.5010(8)	0.8665(7)	0.3025(4)	0.053(3)
C-2	0.1671(10)	0.9619(11)	0.1951(6)	0.076(4)
C-2A	0.0587(10)	1.0957(12)	0.1493(8)	0.088(4)
C-2A′	−0.0056(11)	1.1319(13)	0.0820(9)	0.158(7)
C-2′	0.5339(8)	1.0505(7)	0.1870(4)	0.048(2)
C-2′B	0.5975(9)	1.0522(8)	0.0765(4)	0.058(3)
C-2′B′	0.6766(12)	1.0977(11)	0.0259(6)	0.108(5)
C-2″	0.6271(7)	0.8792(7)	0.2949(4)	0.045(2)
C-2″A	0.7500(11)	0.8642(10)	0.2023(6)	0.073(3)
C-2″A′	0.7889(14)	0.8038(10)	0.1533(6)	0.119(6)
C3″	0.6897(9)	0.8418(7)	0.3587(5)	0.057(3)
C3″B	0.8383(11)	0.9551(12)	0.3667(5)	0.071(3)
C3″B′	0.9672(11)	0.9669(15)	0.3550(7)	0.155(8)
C-4A	0.2400(10)	0.7633(8)	0.2732(5)	0.064(3)
C-4A′	0.1781(10)	0.6881(8)	0.2364(6)	0.077(3)
C-4′B	0.4652(8)	1.0800(8)	0.3489(5)	0.055(3)
C-4′B′	0.5195(10)	1.1748(7)	0.3639(4)	0.064(3)
C-4″	0.6791(10)	0.7319(8)	0.3618(4)	0.068(3)
C-4″C	0.6681(11)	0.6795(10)	0.4722(6)	0.071(3)
C-4″C′	0.7271(16)	0.6300(10)	0.5250(6)	0.129(6)
C-5	0.3057(8)	0.9322(6)	0.2845(4)	0.046(2)
C-5′	0.4326(7)	0.9440(6)	0.2700(4)	0.039(2)

U_{eq} is defined as one third of the trace of the orthogonalized U_{ij} tensor.
[a] Atoms in the table numbered as indicated in Fig. 1.

and also because a more stable incipient tertiary carbocation is formed. The ring closure is then effected by attack of the sulfur at this cationic center. As shown in Scheme 1, the approach of sulfur should occur preferentially from one of the faces of the cation, as the other is hindered by the acetoxy group at C-4. In this way, the ring formation leads to the stereocenter at C-2 of the original bis(thiosemicarbazone) having the *R* configuration. The second ring closure should also occur via a cation that possesses one of the faces somewhat hindered by the vicinal heterocycle, which accounts for the slight predominance (1.2:1 ratio) of the 5*R* diastereomer **2** over the 5*S* (**3**).

3. Experimental

General methods.—^{1}H and ^{13}C NMR spectra were recorded at 200 or 500 MHz and 50 or 125 MHz, respectively, in pyridine-d_5 solutions. Data are shown in Tables 1 and 2. Optical rotations were recorded at 20 °C, and the melting points are uncorrected. Elemental analyses were performed by UMYMFOR, CONICET-University of Buenos Aires, Argentina. Chromatographic purification was performed on Silica Gel G using mixtures of cyclohexane and EtOAc as eluent. The data for the structure resolution was gathered with a Siemens P4 diffractometer on a crystal of $0.44 \times 0.28 \times 0.12$ mm, the best out of a large number of samples were scrutinized, all showing a distinctive weak diffracting power. Measurements were performed at room temperature and a summary of the experimental details is presented in Table 3. The structure was solved by direct methods and difference Fourier techniques, and refined by full-matrix least-squares on F^2, using the SHELXL97 package. Due to the rather poor quality of the data available, only non-H atoms could be found and refined. For the H atoms, those unambiguously defined by the stereochemistry were positioned at their expected site and allowed to ride onto the non-H atoms to which they were attached, with an isotropic displacement factor 1.2 times (1.5 for terminal methyl groups) larger than the isotropic equivalent of their host's; those pertaining to the disordered water molecule, instead, could not be guessed and accordingly were not included in the final model. The correct handedness of the structure was determined by refinement of the Flack parameter *F* (ideal values: 0 for the correct structure, 1 for the inverted one). Final values for R_1, wR_2 and *F* [0.064, 0.168, 0.00 (27); 0.066, 0.172, 0.73 (27)] unambiguously confirmed the former as the correct stereoisomer.

*(5*R*,5′*R*)-2,2′-Diacetamido-4,4′-di-*N*-acetyl-5′-(1-deoxy-2,3,4-tri-*O*-acetyl-*D*-erythritol-1-yl)-5,5′-bis-(1,3,4-thiadiazoline)* (**2**) *and its (5*S*,5′*R*)-diastereomer* **3**.—A solution of bis(thiosemicarbazone) **1** (0.64 g, 2.10 mmol) in pyridine (5 mL) and acetic anhydride (5 mL) was stirred overnight ($\sim$16 h) at rt. Ethanol (5 mL) was added and the stirring maintained for an additional 1 h. The mixture was concentrated with occasional addition of toluene to eliminate pyridine and AcOH. The resulting syrup crystallized from MeOH. Two recrystallizations from the same solvent afforded **2**

(0.36 g, 28.6% yield): mp 236–237 °C; $[\alpha]_D^{20}$ +265.2° (*c* 1, $CHCl_3$); ^1H NMR (C_5D_5N): δ 2.40–1.99 (7 s, 21 H, CH_3); ^{13}C NMR ($CDCl_3$): δ 171.4–169.5 (CO), 23.6–20.4 (CH_3). Anal. Calcd for $C_{22}H_{30}N_6O_{10}S_2$: C, 43.85; H, 4.98; N, 13.95; S, 10.63. Found: C, 43.73; H, 5.06; N, 13.88; S, 10.58.

Crystals of **2** suitable for X-ray diffraction analysis were grown from a diluted solution of **2** (0.10 g) in 90% aqueous methanol, which was left at room temperature for many days.

The mother liquors of crystallization and recrystallization of **2** were concentrated and the residue (0.86 g) was flash chromatographed with 3:2 cyclohexane–EtOAc. Concentration of the less polar fraction afforded a mixture of **2** + **3** (0.44 g, 35% yield), in approximately 1:5.5 ratio (estimated from ^{13}C NMR spectrum). The solid mass (**2** + **3**) was partially dissolved in acetone, where compound **3** had a higher solubility. Evaporation of the solvent and recrystallization from EtOAc afforded **3**: mp 221–222 °C; $[\alpha]_D^{20}$

Table 5
Selected interatomic bond lengths (Å), angles (°) and torsion angles (°) for **2** [a]

Bond lengths			
S-1–C-2	1.788(14)	N-3′–N-4′	1.391(10)
S-1–C-5	1.845(9)	N-4′–C-5′	1.511(11)
S-1′–C-2′	1.759(10)	C-1″–C-5′	1.500(12)
S-1′–C-5′	1.841(8)	C-1″–C-2″	1.509(13)
N-3–C-2	1.23(2)	C-2″–C-3″	1.588(12)
N-3–N-4	1.411(11)	C-3″–C-4″	1.528(14)
N-4–C-5	1.451(11)	C-5–C-5′	1.538(12)
N-3′–C-2′	1.288(10)		
Bond angles			
C-2–S-1–C-5	86.6(5)	O-3″B–C-3″–C-2″	109.4(8)
C-2′–S-1′–C-5′	90.1(4)	C-4″–C-3″–C-2″	108.8(8)
C-2–N-3–N-4	108.3(10)	O-4″C–C-4″–C-3″	111.4(8)
N-3–N-4–C-5	117.0(7)	N-4–C-5–C-5′	112.7(8)
C-2′–N-3′–N-4′	109.5(7)	N-4–C-5–S-1	103.1(6)
N-3′–N-4′–C-5′	118.4(6)	C-5′–C-5–S-1	114.5(6)
C-5′–C-1″–C-2″	113.7(8)	C-1″–C-5′–N-4′	112.2(7)
N-3–C-2–S-1	120.6(10)	C-1″–C-5′–C-5	111.3(7)
N-3′–C-2′–S-1′	118.5(7)	N-4′–C-5′–C-5	111.1(7)
O-2″A–C-2″–C-1″	111.9(8)	C-1″–C-5′–S-1′	111.4(6)
O-2″A–C-2″–C-3″	107.6(7)	N-4′–C-5′–S-1′	101.5(5)
C-1″–C-2″–C-3″	109.7(8)	C-5–C-5′–S-1′	108.9(6)
O-3″B–C-3″–C-4″	105.9(9)		
Torsion angles			
C-2–N-3–N-4–C-5	−18.9(12)	C-2–S-1–C-5–C-5′	107.1(7)
C-2′–N-3′–N-4′–C-5′	7.7(10)	C-2″–C-1″–C-5′–N-4′	−49.7(10)
N-4–N-3–C-2–S-1	4.1(12)	C-2″–C-1″–C-5′–C-5	−175.0(8)
C-5–S-1–C-2–N-3	7.8(9)	C-2″–C-1″–C-5′–S-1′	63.3(9)
N-4′–N-3′–C-2′–S-1′	3.8(10)	N-3′–N-4′–C-5′–C-1″	105.0(8)
C-5′–S-1′–C-2′–N-3′	−10.5(8)	N-3′–N-4′–C-5′–C-5	−129.7(7)
C-5′–C-1″–C-2″–O-2″A	−94.7(10)	N-3′–N-4′–C-5′–S-1′	−14.0(8)
C-5′–C-1″–C-2″–C-3″	145.9(8)	N-4–C-5–C-5′–C-1″	−73.8(9)
O-2″A–C-2″–C-3″–O-3″B	63.0(10)	S-1–C-5–C-5′–C-1″	168.8(6)
C-1″–C-2″–C-3″–O-3″B	−175.1(8)	N-4–C-5–C-5′–N-4′	160.4(6)
O-2″A–C-2″–C-3″–C-4″	−52.3(10)	S-1–C-5–C-5′–N-4′	43.0(8)
C-1″–C-2″–C-3″–C-4″	69.7(11)	N-4–C-5–C-5′–S-1′	49.4(8)
O-3″B–C-3″–C-4″–O-4″C	65.2(11)	S-1–C-5–C-5′–S-1′	−68.0(7)
C-2″–C-3″–C-4″–O-4″C	−177.3(7)	C-2′–S-1′–C-5′–C-1″	−107.4(7)
N-3–N-4–C-5–C-5′	−100.7(9)	C-2′–S-1′–C-5′–N-4′	12.1(6)
N-3–N-4–C-5–S-1	23.3(9)	C-2′–S-1′–C-5′–C-5	129.4(7)
C-2–S-1–C-5–N-4	−15.7(6)		

[a] Atoms in the table numbered as indicated in Fig. 1.

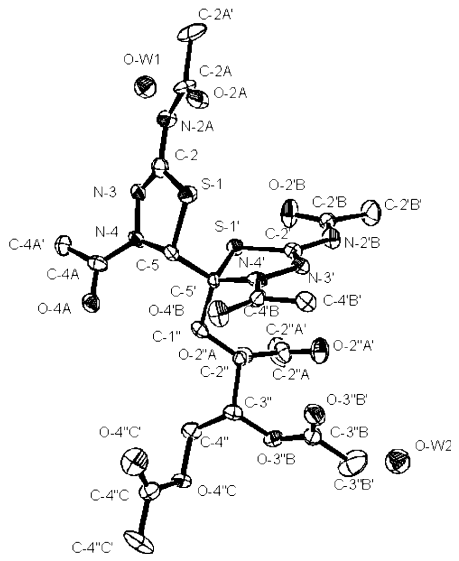


Fig. 1. Molecular structure of **2** showing 30% probability thermal ellypsoids using ORTEP.

$-179.6°$ (*c* 1.5, EtOH); ^{1}H NMR (C_5D_5N): δ 2.25–1.90 (7 s, 21 H, CH_3); ^{13}C NMR ($CDCl_3$): δ 171.7–169.5 (*C*O), 23.4–20.4 (*C*H_3). Anal. Calcd for $C_{22}H_{30}N_6O_{10}S_2$: C, 43.85; H, 4.98; S, 10.63. Found: C, 44.22; H, 5.15; S, 10.12.

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