Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron: Asymmetry
Tetrahedron: *Asymmetry* 18 (2007) 1486–1494

Molecular self-assembly and optical activity of chiral thionooxalamic acid esters

Barbara Piotrkowska,[a] Maria J. Milewska,[a] Maria Gdaniec[b] and Tadeusz Połoński[a,*]

[a]*Department of Chemistry, Technical University, 80-952 Gdańsk, Poland*
[b]*Faculty of Chemistry, A. Mickiewicz University, 60-780 Poznań, Poland*

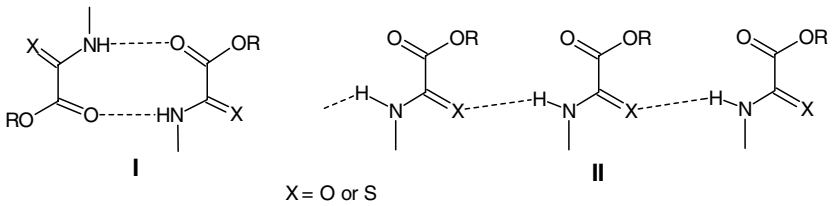
Received 15 May 2007; accepted 18 June 2007

Abstract—Three chiral bisthionooxalamides were synthesized by acylation with ethyl or (1*R*)-menthyl chloroxoacetate of the corresponding diamines and subsequent thionation with Lawesson's reagent. Single crystal X-ray diffraction analysis revealed that products **4b**–**7b** self-assemble in the solid state by the ring [N–H···O=C, $R_2^2(10)$] or chain [N–H···S=C, C(4)] hydrogen-bond motifs. Only in the case of **4b** was a helical superstructure formed. In racemic compound **6b**, the molecules are connected via N–H···S=C hydrogen bonds into homochiral chains, similar to those formed in **7b**. The solid state CD spectra of chiral bisthionooxalamides are characterized by strong Cotton effects in the region of the thioamide n–π* transition. Their sign is determined by the helicity of the S=C–C=O unit.

1. Introduction

The construction of complex supramolecular architectures by the self-assembly of a molecular species via weak non-covalent interactions in the solid state is the main goal of crystal engineering.[1] Particularly, attractive targets are helical assemblies that are indispensable structural elements in biological systems. The helical organization of molecules is an ubiquitous phenomenon in Nature and appears to play a critical role in molecular recognition and information storage.[2] In view of the importance of helical chirality as a structural motif, there have been many efforts to introduce helicity into artificial systems.[3] The construction of such systems by self-assembly is a promising alternative to a stepwise covalent synthesis. Among the variety of intermolecular interactions, relatively strong and directional hydrogen bonds appear to be the most important driving force for stabilizing a supramolecular structure. They can result in the formation of one-dimensional chains or tapes, two-dimensional sheets or layers and various three-dimensional structures.

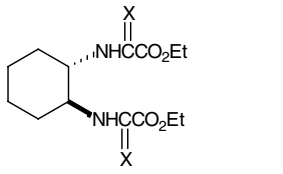
To explore the possibility of a helix supramolecular architecture, we chose oxalamic esters due to their ability to form self-complementary hydrogen-bonding interactions, motif **I**,[4] very similar to that known for simple oxalamides,[5] which have found wide application as supramolecular building blocks for construction of ordered solid state assemblies,[5,6] *meso*-helicate structures,[7] and gelators yielding thermo-reversible gels.[8] A Cambridge Structural Database (CSD)[9] survey revealed that oxalamic esters also readily form chain motif **II**[10] involving only amide units. In contrast to oxalamides organizing into polymeric tape structures, simple oxalamic acid esters can form only dimers with the use of the hydrogen-bond motif **I**. Thus compounds bearing at least two such functions are required for



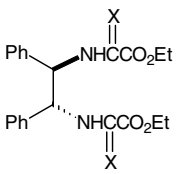
* Corresponding author. Tel.: +48 58 3471528; fax: +48 58 3472694; e-mail: tadpol@chem.pg.gda.pl

0957-4166/$ - see front matter
doi:10.1016/j.tetasy.2007.06.019

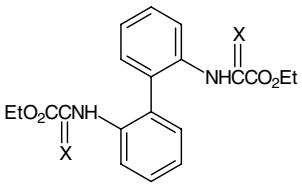
the construction of polymeric assemblies with use of this cyclic motif. We expected that upon acylation, *trans*-1,2-diaminocyclohexane **1**, 1,2-diphenylethylenediamine **2**, and 2,2′-diaminobiphenyl **3** residues may serve as scaffolds to create helical hydrogen-bonded structures. To assure us of obtaining homochiral supramolecular assemblies, we used optically active amines **1** and **2**, whereas in the case of **3**, the acylation was carried out with the use of the chiral acid chloride. We also anticipated that substitution of the amide carbonyl oxygen by sulfur should enhance the acidity of the amide proton making it a stronger hydrogen-bond donor and additionally should promote formation of the cyclic motif **I** since the thiocarbonyl sulfur atom is a much weaker hydrogen-bond acceptor than the carbonyl oxygen. Substitution of O for S, causes bathochromic shifts of the corresponding UV and CD bands, facilitating the spectroscoping measurements.[11] Thus, we designed and synthesized thionooxamides **4b**–**7b** and examined their ability to generate helical networks in the solid state by single crystal X-ray analysis and CD measurements.



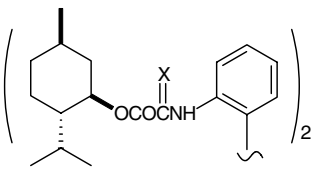
4a, X = O
4b, X = S



5a, X = O
5b, X = S



6a, X = O
6b, X = S



7a, X = O
7b, X = S

2. Results and discussion

Bisoxalamide esters **4a**–**6a** were obtained by acylation of the corresponding diamines with ethyl chlorooxoacetate. Compound **7a** was prepared via the use of (1*R*)-menthyl chloroxoacetate obtained from (−)-menthol and oxalyl chloride. Thionation of compounds **4a**–**7a** with Lawesson's reagent[12] in boiling toluene afforded bisthionooxalamides **4b**–**7b**. The reaction occurred selectively at the amide carbonyl, since the ester group is much less reactive to Lawesson's reagent.[12b]

Yellow needles of **4b** were grown from toluene. X-ray structural analysis revealed that crystals of **4b** belong to the hexagonal $P6_422$ space group, with the molecule located at the special position of the C_2 symmetry. The bisthionooxalamide molecule adopts a conformation in which the equatorially oriented NH groups point up and down with respect to the mean cyclohexane ring plane. Within the molecule, the thionooxalamide groups are in close contact and are oriented in an approximately antiparallel manner (Fig. 1a). The thioamide and ester parts of these groups are significantly twisted along the C–C bond with the S=C–C=O torsion angle of −156.8(1)°. The thionoxalamide units generate the intermolecular hydrogen-bond motif **I** through N–H···O=C interaction [hydrogen-bond geometry: N···O 2.968(2) Å; N–H···O 157(1)°] (Fig. 1c). The twisted conformation of the thionooxalamide groups leads to the twisted motif **I**, and prevents short intermolecular contacts, which would be formed between neighboring molecules of **4b** if they were joined by the planar motif **I**. Hydrogen-bonded molecules of **4b** form an extended right-handed helix of the 3_1 symmetry which runs along the *c*-axis and has a pitch of 18.3 Å (Fig. 1b and c).

Compound **5b** crystallizes as a solvate in the orthorhombic $P2_12_12_1$ space group with two molecules of thioxalamic acid ester and one molecule of toluene in the asymmetric part of the unit cell. The molecules of **5b**, which are located in the crystal at general positions, adopt the conformation of an approximate C_2 symmetry, which is mostly broken by the terminal ethyl substituents. Despite a similarity in the molecular symmetry between **4b** and **5b**, a spatial arrangement adopted by thionooxalamide groups is quite different in the two crystal structures: in **5b** the torsion angle along the N–C_{sp^3} bond of the thionooxalamide group is in the range 155.8(4)–166.5(4)° whereas in **4b**, the analogues torsion angle is −94.5(2)°. The conformation adopted by **5b** allows the formation of discrete supramolecular assemblies composed of two symmetry independent molecules joined by a pair of strongly twisted cyclic motifs **I**. These hydrogen-bonded assemblies have an approximate D_2 symmetry (Fig. 2b). The non-planarity of the cyclic motif reflects a strong twist of thionoxalamide units which most probably results from the optimalization of intradimer hydrogen-bonding interactions. The S=C–C=O torsion angle values range from −146.7(3)° to −159.9(3)°.

Whereas compounds **4b** and **5b** are chiral, bisthionooxalamide **6b** is achiral and its orange needle-shaped crystals obtained from toluene belong to the centrosymmetric space group $P\bar{1}$. There are two symmetry independent molecules of **6b** in the crystal, both adopting similar asymmetric conformations with the phenyl rings rotated by 61.6(3)° and 57.5(3)° about the central C–C bond. One thionoxalamide unit is nearly planar whereas the second one is significantly twisted [the corresponding S=C–C=O torsion angles are of 177.6(4)°, 178.1(3)° for planar units and 137.0(3)°, 137.9(3)° for twisted units]. The chiral conformations of the molecules are fixed by the intramolecular N–H···S=C hydrogen bond between the two thionoxalamide ester groups, which in **6b** are separated by three C–C bonds. The N–H groups not involved in the intramolecular interaction act as donors in intermolecular N–H···S=C hydrogen bonding, joining the homochiral molecules of **6b** into infinite chiral chains (Fig. 3b). Thus, in bisthionooxalamide **6b**, only thionamide groups are involved in hydrogen-bonding and motif **II** encompasses both intra- and intermolecular N–H···S=C interactions. In the crystal, there are two symmetry independent chiral chains but since the

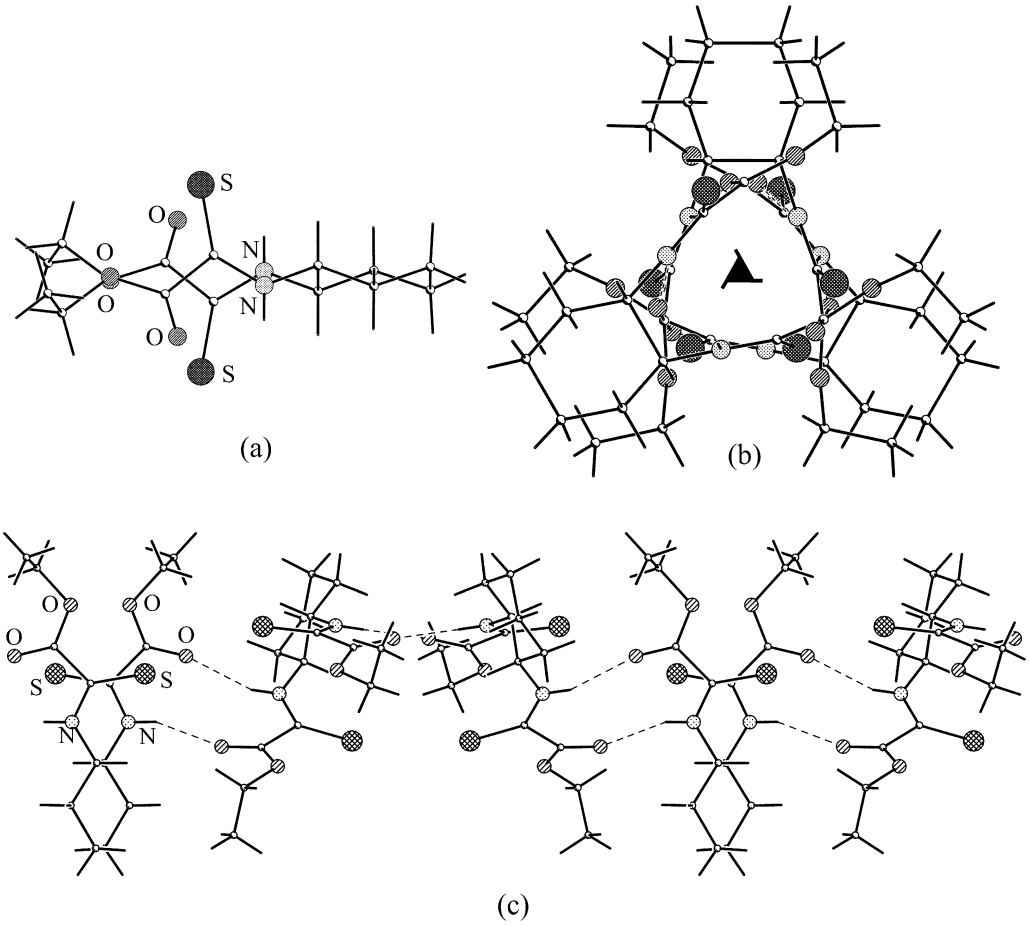


Figure 1. Crystal structure of **4b**: (a) side view of the molecule showing anti-parallel arrangement of the thionooxalamide groups; (b) the right-handed helix via hydrogen bonds—view along the *c*-axis; (c) view perpendicular to the helix axis. Hydrogen bonds are shown as dashed lines.

structure is centrosymmetric, the chains of the opposite chirality co-exist within one crystal lattice.

Compound **7b** (yellow prisms, space group $P2_1$) is the chiral analogue of **6b** with the ester ethyl groups changed to chiral (1*R*,2*S*,5*R*)-menthyl units. The crystal structure of **7b** reveals that the twist angle between the phenyl rings of the core biphenyl, assuming the *P*-helicity, is of 61.2(2)°. Similar to **6b**, the twisted conformation is stabilized by an intramolecular N–H···S=C interaction (Fig. 3a) and molecules related by translation along the *b*-axis are connected via hydrogen bonds into chiral chains (Fig. 3b). In **7b**, the intermolecular three-center hydrogen bonds are formed between the CO and CS groups of the *cis*-oriented thionoxalamide unit (the S=C–C=O dihedral angle is of 13.5(2)°) and the NH hydrogen of the twisted *trans*-thionoxalamide group [the S=C–C=O dihedral angle is of 139.7(2)°] (Fig. 3b).

In order to obtain more information with regards to the formation and helical organization of the aggregates, we studied the UV–vis and CD spectra of the thionooxalamides **4b**–**7b** in the solid state and in solution. The UV–vis spectrum of **4b** taken in the cyclohexane–CH_2Cl_2 (4:1) shows a weak absorption near 440 nm (ε 50), which shifts to ca. 400 nm upon changing the solvent to methanol. Thus it can be unequivocally assigned to the n–π^* electronic transition. A much stronger absorption at 300 nm (ε 11,000) is only slightly dependent on the solvent polarity changes and corresponds to the allowed π–π^* excitation. Compounds **5b** and **7b** behave in a similar manner. Interactions between two carbonyl or thiocarbonyl groups result in the splitting of the n, π, and π^* levels.[13] However, in monothiooxamides the carbonyl and thiocarbonyl n as well as π levels have rather different energies and their interaction is much weaker.[14] In fact, the two lowest energy transitions occur at much shorter wavelengths than those observed in dithiooxamides and the UV–vis spectra of monothiooxamides resemble those of simple thioamides. The twisted oxamide and dithiooxamide systems are inherently chiral while the sign of the CD band corresponding to the lowest energy n–π^* transition is determined by helicity of these chromophores. Thus the right-handed chirality (*P*-helicity) of the twisted chromophore should lead to the negative Cotton effect at the region of the n–π^* excitation and left-handed chirality (*M*-helicity) to the positive one.[13d,15] An analogous behavior is also expected for monothiooxamides. The solid state CD of **4b**, measured in a KBr disk shown in Figure 4, featured a strong positive Cotton effect near 460 nm in accordance with the X-ray structure revealing the left-handed twist of the thionoxalamide unit. Obviously, upon dissolution of the crystal, the helical structure

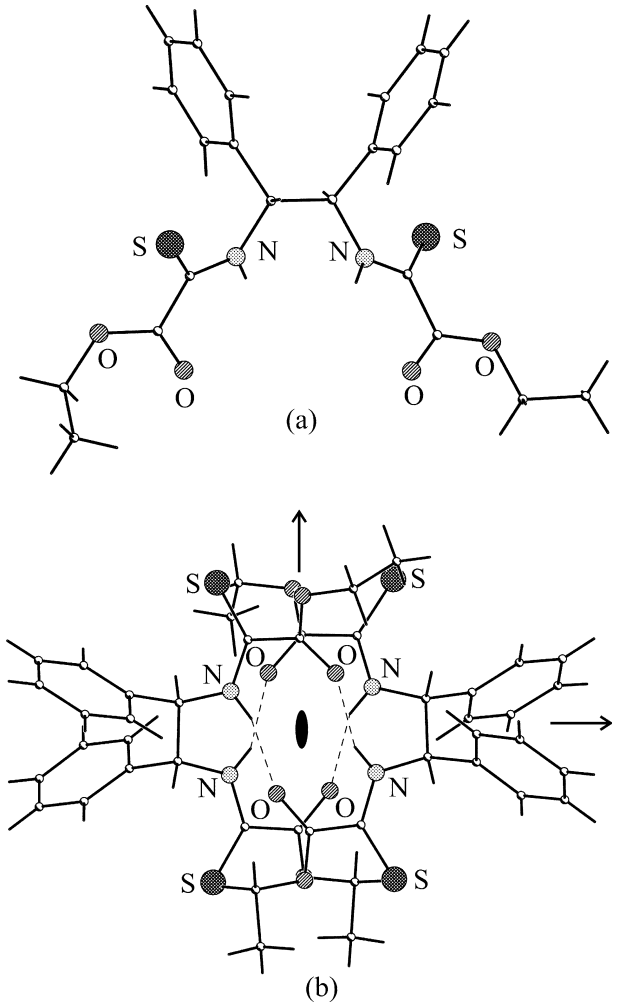


Figure 2. Crystal structure of **5b**: (a) conformation adopted one of the symmetry independent molecules of **5b** in the crystal and (b) hydrogen-bonded dimeric assembly formed by the two symmetry independent molecules of **5b** showing an approximate D_2 symmetry (with indicated directions of pseudo twofold axes). Hydrogen bonds are shown as dashed lines.

is lost which results in a decrease in the long-wavelength CD signal, which moves to shorter wavelengths and inverts the sign. The latter effect indicates that the *P*-helicity of the chromophore predominates in solution. In contrast, a strong positive Cotton effect at 450 nm exhibited by **5b** in the solid state also persists in solution (Fig. 5), which means that the helical dimer structure is at least partially preserved in solution. A moderately strong CD near 470 nm observed in a non-polar solvent splits into two overlapping positive bands at 420 and 380 nm upon changing the solvent to methanol and that might be due to a contribution from two species with different degree of the chromophore twist. They are most likely responsible for the two negative Cotton effects observed in the region of the π–π^* excitation.

The lack of helical organization of the molecules of bisthionooxalamide **7b** results only in weak Cotton effects in the solid state as well as in solution CD spectra (Fig. 6). There are two weak negative CD bands near 450 and 400 nm in the solid state spectrum corresponding to the n–π^* transition in the nearly planar *cis*- and twisted *trans*-thionooxalamide group, respectively, assuming *P*-helicity. The solution spectra appeared to be extremely sensitive to solvent polarity and feature an exciton couplet[16] in the region of the π–π^* transition; a positive one in cyclohexane–CH_2Cl_2 and a negative one in methanol. They correspond to the right- and left-handed screwness, respectively, of the transition moments of the chromophores assuming two mutual different orientations induced by solvent changes in the conformationally flexible molecule of **7b**.

3. Conclusion

In conclusion, our results have shown that bisthionooxalamides are supramolecular monomers with a potential to self-associate through intermolecular hydrogen bonds into helices in the solid state. Using optically active monomers the crystalline homochiral, infinite as well as discrete supramolecular assemblies can be prepared. However, the intermolecular N–H···O=C hydrogen bonds formed by two oxalamide functions are generally weaker than those involving two simple amide groups,[17] which makes the prediction and control of the three-dimensional structure of the aggregates rather difficult. The long-wavelength absorption of the thionooxalamide chromophore facilitates the monitoring of the conformational changes within the molecules with use of the solid state and solution CD measurements.

4. Experimental

^{1}H and ^{13}C NMR spectra were obtained with a Varian Unity Plus spectrometer at 500 and 125 MHz, respectively. The deuteriated solvents were used as an internal lock for ^{1}H and ^{13}C NMR. FT-IR absorptions were taken with a Bruker IFS66 spectrometer. CD spectra were recorded on a JASCO J-715 dichrograph. The solid state CD spectra were taken in freshly prepared KBr disk. A mixture of 3 mg of the sample and 200 mg of dried KBr was ground and formed into a disk 0.5 mm thick and with a radius of 15 mm. The disk was rotated around the optical axis and the CD recordings were made for several positions in order to check a reproducibility of the spectrum. The solution CD spectra were taken using 1 and 0.5 mm path lengths and sample concentration of 0.001–0.005 mol L^{-1}. The UV–vis spectra were measured with Unicam SP-300 spectrophotometer.

4.1. (1*S*,2*S*)-*N*,*N*′-1,2-Cyclohexanediyl-bis-oxalamic acid diethyl ester, 4a

To a solution of (1*S*,2*S*)-(+)-1,2-diaminocyclohexane **1**[18] (2.09 g, 18.3 mmol) in chloroform (35 mL), ethyl chlorooxoacetate (4.07 mL, 36.7 mmol) and triethylamine (5.7 mL, 41 mmol) were added and the mixture was kept at room temperature overnight. The reaction mixture was washed with water, dilute hydrochloric acid, and saturated aqueous $NaHCO_3$. The organic layer was dried over

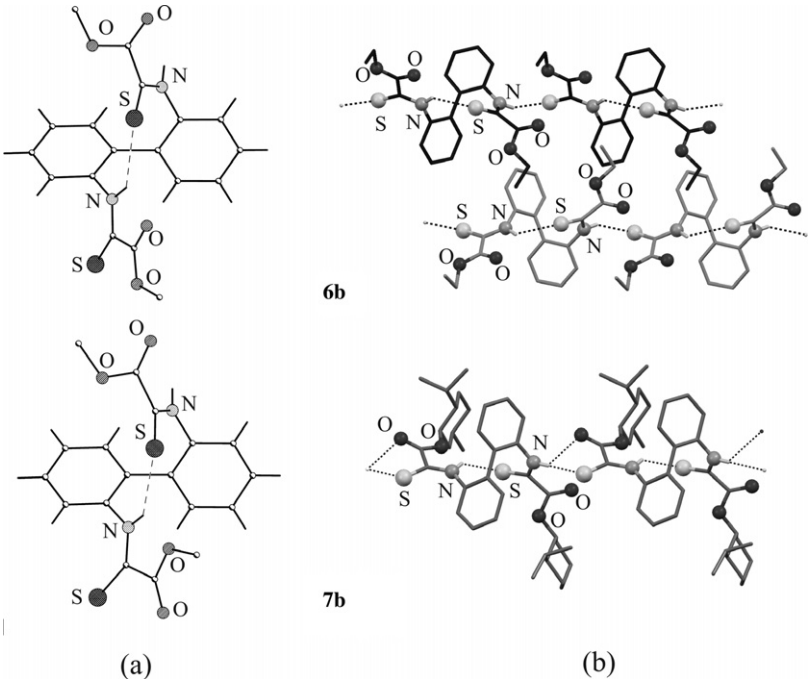


Figure 3. Comparison of crystal structures of the biphenyl derivatives **6b** and **7b**: (a) asymmetric conformations with intramolecular hydrogen bonds (alkyl substituents omitted for clarity)—the *cis*-oriented thionoxalamide group in **7b** should be noted; (b) chiral chains in the racemic **6b** (the two chains of opposite chirality are symmetry independent) and in chiral **7b**.

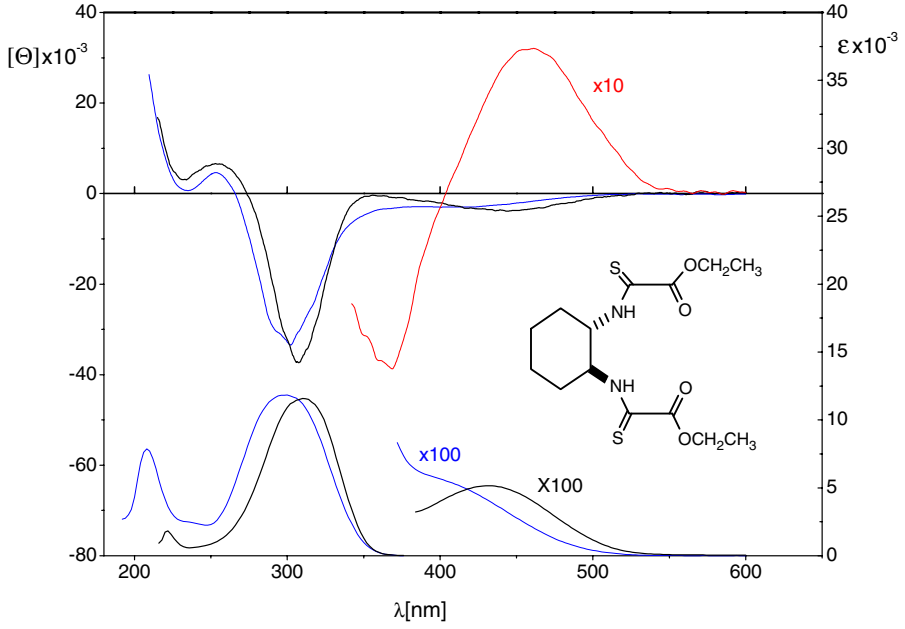


Figure 4. Solid state and solution CD and UV–vis spectra of **4b** taken in a KBr disk, cyclohexane–CH_2Cl_2 (4:1) and MeOH (red, black, and blue lines, respectively).

$MgSO_4$ and then evaporated at reduced pressure. The resulting solid was recrystallized from chloroform–hexane to obtain the product as white needles (3.5 g, 60%); mp 150.5–152 °C; $[\alpha]_D^{25} = -31$ (c 1.168, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 7.3 (br s, NH, 2H), 4.34 (m, 4H), 3.8 (s, 2H), 2.11 (d, $J = 6.3$ Hz, 2H), 1.83 (s, 2H), 1.38 (t, $J = 7.1$ Hz, 10H); ^{13}C NMR ($CDCl_3$) δ 160.1, 156.8, 63.1, 53.5, 31.7, 24.3, 13.8; ν_{max} (KBr) 3370, 3314, 1729, 1704, and 1679 cm^{-1}. Anal. Calcd for $C_{14}H_{22}N_2O_6$ (314): C, 53.50; H, 7.05; N, 8.91. Found: C, 53.38; H, 6.95; N, 8.82.

4.2. (1*S*,2*S*)-*N*,*N*′-1,2-Cyclohexanediyl-bis-thiooxalamic acid diethyl ester, 4b

A mixture of **4a** (0.985 g, 3.13 mmol) and Lawesson's reagent (1.267 g, 3.13 mmol) in toluene (60 mL) was

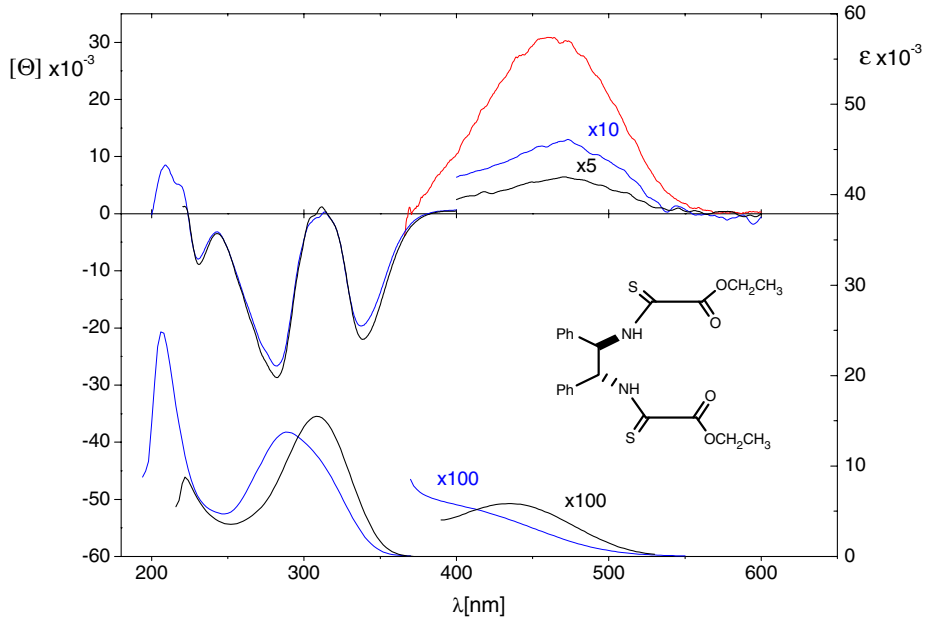


Figure 5. Solid state and solution CD and UV–vis spectra of **5b** taken in a KBr disk, cyclohexane–CH_2Cl_2 (4:1) and MeOH (red, black, and blue lines, respectively).

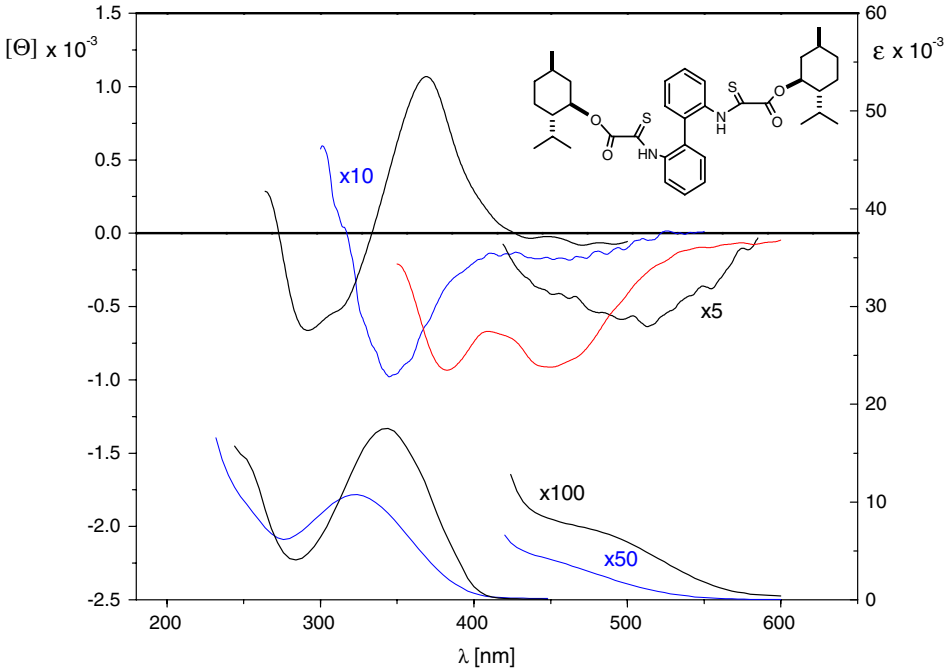


Figure 6. Solid state and solution CD and UV–vis spectra of **7b** taken in a KBr disk, cyclohexane–CH_2Cl_2 (4:1) and MeOH (red, black, and blue lines, respectively).

refluxed for 0.5 h. After removal of the solvent, the residue was purified by column chromatography on silica gel [elution with chloroform–hexane (1:1)]. The product was crystallized from toluene–hexane to give the title compound as yellow needles (0.73 g, 67%); mp 87–88 °C; $[\alpha]_D^{25} = -442$ (*c* 0.052, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 9.18 (s, NH, 2H), 4.63 (br s, 2H), 4.35 (m, 4H), 2.29 (br s, 2H), 1.89 (br s, 2H), 1.45 (d, $J = 7.8$ Hz, 4H), 1.39 (t, $J = 7.1$ Hz, 6H); ν_{max} (KBr) 3293, 1702, 1528, 1269, and 1246 cm^{-1}. Anal. Calcd for $C_{14}H_{22}N_2O_4S_2$ (346.5): C, 48.54; H, 6.39; N, 8.09; S, 18.51. Found: C, 48.54; H, 6.28; N, 8.02; S, 18.68.

4.3. (1*R*,2*R*)-*N*,*N*′-1,2-Diphenyl-1,2-ethanediyl-bis-oxalamic acid diethyl ester, 5a

Compound **5a** was prepared from (1*R*,2*R*)-(+)-1,2-diphenylethylenediamine **2**[19] in a similar manner to that of compound **4a** in 78% yield; mp 178–180 °C; $[\alpha]_D^{25} = -103.8$ (*c*

0.106, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 7.9 (s, NH, 2H), 7.28–7.15 (m, 10H), 5.37 (dd, $J = 5.86$ Hz and 2.45 Hz, 2H), 4.35 (m, 4H), 1.38 (t, $J = 7.3$ Hz, 6H); ^{13}C NMR ($CDCl_3$) δ 160.0, 156.8, 136.9, 128.6, 128.2, 127.5, 63.2, 58.8, 13.8; ν_{max} (KBr) 3591, 3299, 1742, and 1675 cm^{-1}. Anal. Calcd for $C_{22}H_{24}N_2O_6$ (412): C, 64.07; H, 5.86; N, 6.79. Found: C, 64.01; H, 5.94; N, 6.77.

4.4. (1*R*,2*R*)-*N*,*N*′-1,2-Diphenyl-1,2-ethanediyl-bis-thiooxalamic acid diethyl ester, 5b

Bisthionooxalamide **5b** was obtained in a similar manner to that of compound **4b**. The product was isolated by chromatography on silica gel with chloroform as an eluent and after crystallization from toluene, was obtained as a 2:1 solvate with toluene, yield 62%; mp 76–79 °C; $[\alpha]_D^{25} = -155.6$ (*c* 0.045, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 9.67 (br s, NH, 2H), 7.31–7.24 (m, 10H), 6.19 (dd, $J = 5.9$ Hz and 2.9 Hz, 2H), 4.37 (m, 4H), 1.39 (t, $J = 7.1$ Hz, 6H); ^{13}C NMR ($CDCl_3$) δ 184.0, 158.7, 135.5, 128.9, 128.8, 128.0, 63.2, 63.1, 13.8; ν_{max} (KBr) 3236, 1739, 1726, 1516, and 1270 cm^{-1}. Anal. Calcd for $C_{22}H_{24}N_2O_4S_2$ (444.5): C, 59.44; H, 5.44; N, 6.30; S, 14.43. Found: C, 59.19; H, 5.44; N, 6.27; S, 14.51.

4.5. *N*,*N*′-Biphenyl-2,2′-diyl-bis-oxalamic acid diethyl ester, 6a

Compound **6a** was prepared from 2,2′-diaminobiphenyl **3**[20] in a similar manner to that of compound **4a** in 58% yield; mp 143 °C (CH_2Cl_2–hexane); ^1H NMR ($CDCl_3$) δ 8.73 (s, NH, 2H), 8.52 (d, $J = 7.8$ Hz, 2H), 7.56 (td, $J = 8.7$ Hz and 1.9 Hz, 2H), 7.33 (td, $J = 7.6$ Hz and 1.1 Hz, 2H), 7.32 (dd, $J = 7.8$ Hz and 1.7 Hz, 2H), 4.29 (q, $J = 7.2$ Hz, 4H), 1.32 (t, $J = 7.1$ Hz, 6H); ν_{max} (KBr) cm^{-1} 3348, 1707, 1531, 1290 cm^{-1}. Anal. Calcd for $C_{20}H_{20}N_2O_6$ (394): C, 62.50; H, 5.24; N, 7.29. Found: C, 62.39; H, 5.26; N, 7.20.

4.6. *N*,*N*′-Biphenyl-2,2′-diyl-bis-thiooxalamic acid diethyl ester, 6b

Bisthionooxalamide **6b** was obtained in a similar manner to that of compound **4b**. The product was isolated by chromatography on silica gel with benzene as an eluent; yield 66%; mp 139–140 °C (CH_2Cl_2–hexane); ^1H NMR ($CDCl_3$) δ 10.27 (s, NH, 2H), 8.52 (d, $J = 8.3$ Hz, 2H), 7.54 (td, $J = 8.5$ Hz and 1.5 Hz, 2H), 7.42 (td, $J = 7.6$ Hz and 0.98 Hz, 2H), 7.34 (dd, $J = 7.8$ Hz and 1.5 Hz, 2H), 4.28 (q, $J = 7.1$ Hz, 4H), 1.32 (t, $J = 7.3$ Hz, 6H); ν_{max} cm^{-1} 3421, 3131, 1718, 1365, 1275, and 1261 cm^{-1}. Anal. Calcd for $C_{20}H_{20}N_2O_4S_2$ (416.5): C, 57.68; H, 4.84; N, 6.72; S, 15.40. Found: C, 57.43; H, 4.81; N, 6.75; S, 15.28.

4.7. *N*,*N*′-Biphenyl-2,2′-diyl-bis-oxalamic acid di-(1*R*,2*S*,5*R*)-menthyl ester, 7a

A solution of oxalyl chloride (2.1 mL, 25 mmol) in dichloromethane (10 mL) was cooled to −10 °C and (−)-menthol (3.9 g, 25 mmol) in dichloromethane (10 mL) was then added with stirring and cooling. The reaction mixture was left to stand for 10 h at room temperature and then the solvent was evaporated at reduced pressure. The residue was distilled in vacuo; the fraction boiling at 120–125 °C (15 mmHg) was collected to give (1*R*,2*S*,5*R*)-menthyl chlorooxoacetate;[21] yield 70%, $[\alpha]_D^{22} = -82.4$ (neat).

Compound **7a** was prepared from 2,2′-diaminobiphenyl **3** and freshly prepared (1*R*,2*S*,5*R*)-menthyl chlorooxoacetate in a similar manner to that of compound **4a** in 60% yield; mp 134–136 °C (CCl_4); $[\alpha]_D^{25} = -82.8$ (*c* 0.169, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 8.77 (s, NH, 2H), 8.59 (dd, $J = 8.1$ Hz and 2.2 Hz, 2H), 7.56 (t, $J = 7.6$ Hz, 2H), 7.35 (m, 4H), 4.75 (t, $J = 10.9$ Hz, 2H), 1.95 (d, $J = 8.3$ Hz, 2H), 1.78–1.68 (m, 6H), 1.46 (br t, $J = 10$ Hz, 4H), 1.04 (q, $J = 11.8$ Hz, 4H), 0.91 (d, $J = 6.3$ Hz, 7H), 0.87 (t, $J = 6.3$ Hz, 7H), 0.70 (t, $J = 6.8$ Hz, 6H); ^{13}C NMR δ 159.5, 159.3, 153.8, 134.6, 134.5, 130.1, 126.7, 126.6, 125.6, 121.0, 120.9, 78.4, 46.4, 46.3, 40.1, 39.9, 33.9, 33.8, 31.3, 26.0, 23.1, 21.8, 20.6, 16.0; ν_{max} (KBr) 3308, 1794, 1715, 1700, and 1520 cm^{-1}. Anal. Calcd for $C_{36}H_{48}N_2O_6$ (605): C, 71.50; H, 8.00; N, 4.63. Found: C, 71.28; H, 7.97; N, 4.51.

4.8. *N*,*N*′-Biphenyl-2,2′-diyl-bis-thiooxalamic acid di-(1*R*,2*S*,5*R*)-menthyl ester, 7b

The bisthionooxalamide **7b** was obtained in a similar manner to that of compound **4b**. The product was isolated by column chromatography on silica gel with benzene as an eluent. Yield 59%; mp 228–230 °C (toluene–hexane); $[\alpha]_D^{25} = -150$ (*c* 0.04, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 10.27 (s, NH, 2H), 8.56 (d, $J = 8.3$ Hz, 1H), 8.37 (d, $J = 8.3$ Hz, 1H), 7.54 (q, $J = 7.5$ Hz, 2H), 7.41 (q, $J = 7.3$ Hz, 2H), 7.34 (t, $J = 8.3$ Hz, 2H), 4.73 (m, 2H), 1.96 (br t, $J = 5.2$ Hz, 2H), 1.62 (m, 6H), 1.45 (m, 4H), 1.05 (m, 4H), 0.9 (m, 8H), 0.88 (d, $J = 6.8$ Hz, 3H), 0.83 (d, $J = 6.8$ Hz, 3H), 0.72 (d, $J = 6.8$ Hz, 3H), 0.68 (d, $J = 6.8$ Hz, 3H); ν_{max} (KBr) 3476, 3179, 1747, 1718, 1512, 1275, and 1240 cm^{-1}. Anal. Calcd for $C_{36}H_{48}N_2O_4S_2$ (637): C, 67.89; H, 7.60; N, 4.40; S, 10.06. Found: C, 67.66; H, 7.65; N, 4.46; S, 9.99.

4.9. X-ray structure analysis

Diffraction data were collected using a Kuma CCD diffractometer with graphite monochromated Mo Kα radiation ($\lambda = 0.71073$ Å). The structures were solved by direct methods with the program SHELXS-97.[22] Full matrix least-squares refinement was carried out with SHELXL-97.[23]

Crystal data for **4b**: $C_{14}H_{22}N_2O_4S_2$, $M = 346.46$, hexagonal, space group $P6_422$, $a = b = 12.9170(5)$, $c = 18.2939(7)$ Å, $V = 2643.38(18)$ Å^3, $T = 120$ K, $Z = 6$, μ(Mo Kα) $= 0.320$ mm^{-1}, $\lambda = 0.71073$ Å, 15,300 reflections measured, 1800 unique ($R_{int} = 0.0274$). Final residuals for 104 parameters were $R_1 = 0.0260$, $wR_2 = 0.0573$ for 1782 reflections with $I > 2\sigma(I)$, and $R_1 = 0.0266$, $wR_2 = 0.0576$ for all 1800 data; absolute structure Flack parameter 0.02(8).

Crystal data for **5b**: $(C_{22}H_{24}N_2O_4S_2)_2{\cdot}C_7H_8$, $M = 981.28$, orthorhombic, space group $P2_12_12_1$, $a = 12.3362(15)$, $b =$

12.3866(10), $c = 34.3572(16)$ Å, $V = 5249.9(8)$ Å^3, $T = 120$ K, $Z = 4$, μ(Mo Kα) $= 0.235$ mm^{-1}, $\lambda = 0.71073$ Å, 25,841 reflections measured, 9179 unique ($R_{int} = 0.0785$). Final residuals for 605 parameters were $R_1 = 0.0508$, $wR_2 = 0.0945$ for 9013 reflections with $I > 2\sigma(I)$, and $R_1 = 0.0520$, $wR_2 = 0.0949$ for all 9179 data; absolute structure Flack parameter 0.07(9). The structure was determined from a pseudo-merohedral twinned crystal with the twin matrix [0 1 0 −1 0 0 0 0 1]. The diethyl ether solvate of **5b**, $(C_{22}H_{24}N_2O_4S_2)_2{\cdot}C_4H_{10}O$, is isostructural with **5b** [space group $P2_12_12_1$, $a = 12.5950(13)$, $b = 12.6160(10)$, $c = 33.115(3)$ Å, $V = 5262.0(8)$ Å^3, $T = 130$ K], and also crystallizes as a pseudo-merohedral twin.

Crystal data for **6b**: $C_{20}H_{20}N_2O_4S_2$, $M = 416.50$, triclinic, space group $P\bar{1}$, $a = 9.7779(8)$, $b = 14.1859(11)$, $c = 16.4021(14)$ Å, $\alpha = 112.554(8)$, $\beta = 100.510(7)$, $\gamma = 91.130(6)°$, $V = 2055.8(3)$ Å^3, $T = 293$ K, $Z = 4$, μ(Mo Kα) $= 0.287$ mm^{-1}, $\lambda = 0.71073$ Å, 22,047 reflections measured, 7251 unique ($R_{int} = 0.0498$). Final residuals for 505 parameters were $R_1 = 0.0505$, $wR_2 = 0.1026$ for 3993 reflections with $I > 2\sigma(I)$, and $R_1 = 0.1121$, $wR_2 = 0.1227$ for all 7251 data.

Crystal data for **7b**: $C_{36}H_{48}N_2O_4S_2$, $M = 636.88$, monoclinic, space group $P2_1$, $a = 12.8620(5)$, $b = 9.5611(4)$, $c = 14.3594(5)$ Å, $\beta = 91.432(3)°$, $V = 1765.29(12)$ Å^3, $T = 100$ K, $Z = 2$, μ(Mo Kα) $= 0.0190$ mm^{-1}, $\lambda = 0.71073$ Å, 14,930 reflections measured, 6267 unique ($R_{int} = 0.0159$). Final residuals for 405 parameters were $R_1 = 0.0322$, $wR_2 = 0.0843$ for 5869 reflections with $I > 2\sigma(I)$, and $R_1 = 0.0346$, $wR_2 = 0.0861$ for all 6267 data; absolute structure Flack parameter −0.05(5).

Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 646359–646362. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

Acknowledgments

We are indebted to Dr. J. Frelek (IChO PAN, Warsaw) for CD measurements with use of her JASCO J-715 instrument. The financial support from the Committee of Scientific Research (Project No. 3 T09A 030 29) is gratefully acknowledged.

References

1. (a) Desiraju, G. R. *Crystal Engineering: The Design of Organic Solids*; Elsevier: Amsterdam, 1989; (b) *The Crystal as a Supramolecular Entity*; Desiraju, G. R., Ed.; Wiley: Chichester, 1995; (c) Lehn, J.-M. *Supramolecular Chemistry: Concepts and Perspectives*; VCH: Weinheim, 1995; (d) *Organic Molecular Solids. Properties and Applications*; Jones, W., Ed.; CRC Press: Boca Raton, 1997; (e) Chin, D. N.; Zerkowski, J. A.; MacDonald, J. C.; Whitesides, G. M. In *Organised Molecular Assemblies in the Solid State*; Whitesell, J. K., Ed.; Wiley: Chichester, 1999; Chapter 5; (f) Moulton, B.; Zaworotko, M. J. *Chem. Rev.* **2001**, *101*, 1629.
2. (a) Schulz, G. E.; Schirmer, R. H. *Principles of Protein Structure*; Springer: New York, 1979; Chapter 5; (b) Saenger, W. *Principles of Nucleic Acid Protein Structure*; Springer: New York, 1984; Chapters 10 and 11.
3. (a) Katz, T. J. *Angew. Chem., Int. Ed.* **2000**, *39*, 1921; (b) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893; (c) Albrecht, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 6448; (d) Piguet, C.; Bernardinelli, G.; Hopfgartner, G. *Chem. Rev.* **1997**, *97*, 2005.
4. Garcia-Baez, E. V.; Gomez-Castro, C. Z.; Hopfl, H.; Martinez-Martinez, F. J.; Padilla-Martinez, I. I. *Acta Crystallogr., Sect. C* **2003**, *59*, o541; Blay, G.; Fernandez, I.; Pedro, J. R.; Ruiz-Garcia, R.; Munoz, M. C.; Cano, J.; Carrasco, R. *Eur. J. Org. Chem.* **2003**, 1627.
5. (a) Coe, S.; Kane, J. J.; Nguyen, T. L.; Toledo, L. M.; Wininger, E.; Fowler, F. W.; Lauher, J. W. *J. Am. Chem. Soc.* **1997**, *119*, 86; (b) Nguyen, T. L.; Scott, A.; Dinkelmeyer, B.; Fowler, F. W.; Lauher, J. W. *New J. Chem.* **1998**, 129; (c) Nguyen, T. L.; Fowler, F. W.; Lauher, J. W. *J. Am. Chem. Soc.* **2001**, *123*, 11057.
6. (a) Simonov, Y. A.; Fonari, M. S.; Zaworotko, M. J.; Abourahma, H.; Lipkowski, J.; Ganin, E. V.; Yavolovskii, A. A. *Org. Biomol. Chem.* **2003**, *1*, 2922; (b) Fonari, M. S.; Simonov, Y. A.; Croitoru, L.; Basok, S. S.; Ganin, E. V.; Lipkowski, J. *J. Mol. Struct.* **2006**, *794*, 110; (c) Hsu, Y.-F.; Chen, J.-D. *Eur. J. Inorg. Chem.* **2004**, 1488.
7. Blay, G.; Fernandez, I.; Pedro, J. R.; Ruiz-Garcia, R.; Carmen-Munoz, M.; Cano, J.; Carrasco, R. *Eur. J. Org. Chem.* **2003**, 1627.
8. (a) Makarević, J.; Jokić, M.; Perić, B.; Tomisić, V.; Kojić-Prodić, B.; Zinić, M. *Chem. Eur. J.* **2001**, *7*, 3328; (b) Makarević, J.; Jokić, M.; Frkanec, L.; Katalenić, D.; Zinić, M. *Chem. Commun.* **2002**, 2238; (c) Makarević, J.; Jokić, M.; Raza, Z.; Stefanić, Z.; Kojić- Prodić, B.; Zinić, M. *Chem. Eur. J.* **2003**, *9*, 5567.
9. Allen, F. H. *Acta Crystallogr., Sect. B* **2002**, *58*, 380.
10. (a) Kocienski, P.; Narquizian, R.; Raubo, P.; Smith, C.; Farrugia, L. J.; Muir, K.; Boyle, F. T. *J. Chem. Soc., Perkin. Trans. 1* **2000**, 2357; (b) Hashmi, A. S. K.; Weyrauch, J. P.; Frey, W.; Bats, J. W. *Org. Lett.* **2004**, *6*, 4391; (c) Padilla-Martinez, I. I.; Chaparro-Huerta, M.; Martinez-Martinez, F. J.; Hopfl, H.; Garcia-Baez, E. V. *Acta Crystallogr., Sect. E* **2003**, *59*, o825; (d) Martinez-Martinez, F. J.; Maya-Lugardo, P.; Garcia-Baez, E. V.; Hopfl, H.; Hernandez-Diaz, J.; Padilla-Martinez, I. I. *Acta Crystallogr., Sect. E* **2005**, *61*, o2994.
11. (a) Clouthier, D. J.; Moule, D. C. *Top. Curr. Chem.* **1989**, *150*, 167; (b) Maciejewski, A.; Steer, R. P. *Chem. Rev.* **1993**, *93*, 67; (c) Połoński, T.; Milewska, M. J.; Konitz, A.; Gdaniec, M. *Tetrahedron: Asymmetry* **1999**, *10*, 2591.
12. (a) Yde, B.; Yousif, N. M.; Pedersen, V.; Thomsen, J.; Lawesson, S.-O. *Tetrahedron* **1984**, *40*, 2047; For a review see: (b) Cava, M. P.; Levinson, M. J. *Tetrahedron* **1985**, *41*, 5061; (c) Jesberger, M.; Davis, T. P.; Barner, L. *Synthesis* **2003**, 1929.
13. (a) Larson, D. B.; McGlynn, S. P. *J. Mol. Spectrosc.* **1973**, *47*, 469; (b) Mannschreck, A.; Talvitie, A.; Fischer, W.; Snatzke, G. *Monatshefte* **1983**, *114*, 101; (c) Falth, L.; Hakansson, U.; Sandström, J. *J. Mol. Struct.* **1989**, *186*, 239; (d) Isaksson, R.; Liljefors, T. *J. Chem. Soc., Perkin Trans. 2* **1980**, 1815; (e) Połoński, T. *Tetrahedron: Asymmetry* **1994**, *5*, 149.
14. Henriksen, L.; Isaksson, R.; Liljefors, T.; Sandström, J. *Acta Chem. Scand. B* **1981**, *35*, 489.

15. Hug, W.; Wagniere, G. *Tetrahedron* **1972**, *28*, 1241.
16. Woody, R. W. In *Circular Dichroism, Principles and Applications*; Nakanishi, K., Berova, N., Woody, R. W., Eds.; VCH: New York, 1994; Chapter 13.
17. Aleman, C.; Casanovas, J. *J. Mol. Struct. (Theochem)* **2004**, *675*, 9.
18. Galsbøl, F.; Steenbøl, P.; Søndergaard Sørensen, B. *Acta Chem. Scand.* **1972**, *26*, 3605.
19. Saigo, K.; Kubota, N.; Takebayashi, S.; Hasegawa, M. *Bull. Chem. Soc. Jpn.* **1986**, *59*, 931.
20. Lloyd, D.; Dougall, R. H. *J. Chem. Soc.* **1960**, 4136.
21. Hub, L.; Mosher, H. *J. Org. Chem.* **1970**, *35*, 3691.
22. Sheldrick, G. M. *Acta Crystallogr., Sect. A* **1990**, *46*, 467.
23. Sheldrick, G. M. SHELXL-*97. Program for Crystal Structures Refinement from Diffraction Data*; University of Göttingen: Germany, 1997.