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Conformational Studies on [16]aneS₄. Structures of α- and β-[16]aneS₄ ([16]aneS₄ = 1,5,9,13-Tetrathiacyclohexadecane)

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Abstract

Three morphologies – acicular (α), lamellar (β) and columnar (γ) – are observed for crystals of [16]aneS₄ (1,5,9,13-tetrathiacyclohexadecane). The absolute structures of the α and β forms have been determined: the molecular structures are essentially the same but the two forms differ in their crystal packing. α-[16]aneS₄ crystallizes in the orthorhombic space group $Pbc2_1$ while β-[16]aneS₄ crystallizes in the monoclinic space group $P2_1$. The conformation of the molecules is unusual: whereas the other tetrathia macrocycles [12]aneS₄ and [14]aneS₄ have exclusively *exo* S atoms, in [16]aneS₄ only two lie in *exo* positions and this structural feature is related to the chemical properties of the macrocycle. Molecular mechanics calculations have been carried out on selected conformers of [16]aneS₄ and the results compared with the observed crystal structures and with the hydrocarbon analogue, C₁₆H₃₂. γ-[16]aneS₄ appears to crystallize in the orthorhombic space group $Fdd2$ but it suffers from twinning and no structural information could be obtained.

Introduction

Although the trithia macrocycle 1,4,7-trithiacyclononane ([9]aneS₃) adopts an *endo* conformation in which the three S donors are preorganized for facial coordination to metal ion centres (solid-state structure: Glass, Wilson & Setzer, 1980; gas-phase structure: Blom, Rankin, Robertson, Schröder & Taylor, 1991), structure determinations on larger ring tetra-
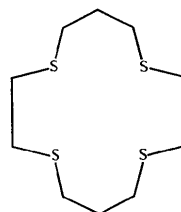
and pentathia analogues have revealed exclusively *exo* conformations. Thus the structures of [12]aneS₄ (1,4,7,10-tetrathiacyclododecane: Robinson & Sangokoya, 1988; Cooper, Foxman, Hartman, Storey & Wolf, 1987), [14]aneS₄ (1,4,8,11-tetrathiacyclotetradecane: DeSimone & Glick, 1976) and [15]aneS₅ (1,4,7,10,13-pentathiacyclopentadecane: Cooper,
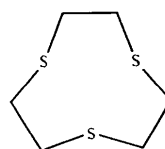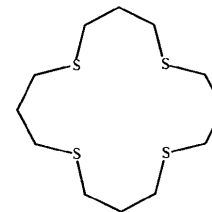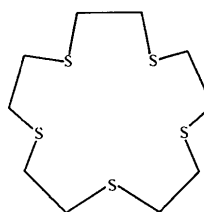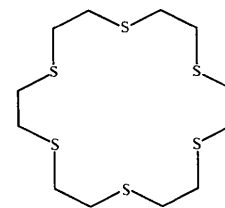

[9]aneS₃
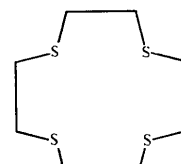
[12]aneS₄

[14]aneS₄

[16]aneS₄

[15]aneS₅

[18]aneS₆

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Foxman, Hartman, Storey & Wolf, 1987) all have their S atoms directed away from the centre of the ring. In contrast, the hexathia macrocycle [18]aneS₆ (1,4,7,10,13,16-hexathiacyclooctadecane: Cooper, Foxman, Hartman, Storey & Wolf, 1987; Cooper, Foxman, Hartman & Wolf, 1983) has four S atoms *exo* and two in *endo* positions. The typical *exo* conformation of the tetrathia macrocycles can be explained by the mutually *gauche* placement of the C—S bonds which minimizes S···S repulsions. This observation provides a rationalization for the tendency of tetrathia macrocycles to coordinate to metal ions in an *exo* manner: *endo* coordination to yield a complex with the metal ion enclosed within the macrocyclic hole requires reorganization of the ligand conformation (DeSimone & Glick, 1976). This preference contrasts sharply with that of [9]aneS₃: the apparent preorganization of this trithia ligand for facial binding to metal centres dominates its coordination chemistry (Blake & Schröder, 1990). Since both *endo* and *exo* coordination of [16]aneS₄ to metal centres has been reported (Blake & Schröder, 1990), we wished to establish the conformation of metal-free [16]aneS₄ and report herein (Halcrow, 1991) the single-crystal X-ray structures of two forms of this tetrathia crown, and relate these data to MM2 molecular mechanics calculations carried out to ascertain the low-energy conformers of this ligand (Grant, Setzer, Tang & VanDerveer, 1991).

Experimental

α form

The polarity of the structure was established using a published procedure (Boelsterli, Eggnauer, Pombo-Villar, Weber, Walkinshaw & Gould, 1991) to identify those reflections which were most sensitive to it: these 21 reflections and their Friedel opposites were collected using Cu Kα X-ray radiation and a structure-factor calculation was carried out using the converged model for each polarity. One polarity gave values for R and wR of 0.0649 and 0.0852 while the other gave values of 0.0540 and 0.0548 and was accordingly adopted. All non-H atoms were allowed anisotropic thermal motion.

β form

At isotropic convergence, final corrections for absorption (minimum 0.735, maximum 1.226) were applied empirically using *DIFABS* (Walker & Stuart, 1983). The structure was refined with anisotropic thermal parameters for S atoms, isotropic for C. The handedness of the structure was determined by the same procedure as described above for the polarity of the α form: using 37 reflections and their Friedel opposites, one enantiomer gave values for R and wR

Table 1. *Experimental details*

	α-[16]aneS₄	β-[16]aneS₄
Crystal data		
Formula	C₁₂H₂₄S₄	C₁₂H₂₄S₄
Source	Diffusion of hexane into a solution in CH₂Cl₂	Diffusion of hexane into a solution in CH₂Cl₂
Colour	Colourless	Colourless
Description	Needle	Plate
Crystal size (mm)	0.96 × 0.15 × 0.10	0.44 × 0.24 × 0.008
M_r	296.56	296.56
Crystal class	Orthorhombic	Monoclinic
Space group	$Pbc2_1$	$P2_1$
a (Å)	17.7366 (17)	5.5605 (19)
b (Å)	9.8219 (7)	8.1240 (22)
c (Å)	9.0558 (11)	17.662 (10)
α (°)	90	90
β (°)	90	96.108 (17)
γ (°)	90	90
V (Å³)	1577.6	793.4
Z	4	2
D_m	Not measured	Not measured
D_x (Mg m⁻³)	1.248	1.241
Radiation	Mo Kα	Cu Kα
λ (Å)	0.71073	1.54184
No. of reflections for lattice parameters	40	20
θ range (°)	14-16 (± ω)	18 22 (± ω)
μ (mm⁻¹)	0.556	5.227
T (K)	298	293
Data collection		
Diffractometer	Stoë Stadi-4 four circle	Stoë Stadi-4 four circle
Scan type	ω 2θ learnt profile (Clegg, 1981)	ω-2θ
Absorption-correction type	None	Semi-empirical
T_{min}	–	0.2905
T_{max}	–	0.4137
Reflections		
Measured	3256	1617
Independent	2576	817
Observed	1985	622
Criteria for observed	$F > 6\sigma(F)$	$F > 4\sigma(F)$
R_{int}	0.018	0.027
θ_{max} (°)	25	50
Standards	3 every 120 min	3 every 120 min
Variation	Insignificant	Insignificant
h_{min}	0	– 5
h_{max}	21	5
k_{min}	0	0
k_{max}	11	8
l_{min}	– 10	– 17
l_{max}	10	17
Refinement		
Treatment of H atoms	In calculated positions with a common U_{iso} = 0.072 (2) Å²	In calculated positions with fixed U_{iso} = 0.08 Å²
Refinement on	F	F
Parameters refined	145	85
R	0.0316	0.0711
wR	0.0429	0.0844
S	1.153	1.153
$(\Delta/\sigma)_{max}$	0.013	0.005
Reflections used	1985	622
Weighting scheme	$w = 1/[\sigma^2(F) + 0.000816F^2]$	$w = 1/[\sigma^2(F) + 0.0013F^2]$
$\Delta\rho_{min}$ (e Å⁻³)	0.21	– 0.55
$\Delta\rho_{max}$ (e Å⁻³)	0.29	0.65
Extinction correction	None	5.95 × 10⁻⁷
Source of atomic scattering factors	*SHELX*76	*SHELX*76

Table 2. *Melting point and mixed melting point data* (°C)

Crystal form	
Acicular (α)	59.5–60.2
Lamellar (β)	57.8 59.0
Columnar (γ)	60.0–60.9
Mixture	
α + β	56.5–57.5
α + γ	55.5–57.0
β + γ	56.5–57.2

Table 3. *Minimized strain energies* (kcal mol⁻¹) *derived using MM2 calculations for the conformers illustrated in Fig. 4*

ΔE is the energy above that of the lowest-energy conformer, A.

| | [16]aneS₄ | | C₁₆H₃₂* | |
Conformation	E	ΔE	E	ΔE
A	12.83	0	16.58	0
B	14.16	+1.33	18.99	+2.41
C	14.74	+1.91	18.69	+2.11
D	13.56	+0.73	19.99	+3.41
E	13.57	+0.74		
F	13.68	+0.85		
G	20.03	+7.20		
H	19.37	+6.54		

* Allinger, Gorden & Profeta (1980).

Table 4. *Molecular geometry* (Å, °) *for* α-[16]aneS₄ *and* β-[16]aneS₄

	α	β
S(1)—C(2)	1.808 (4)	1.790 (18)
S(1)—C(16)	1.816 (4)	1.789 (19)
C(2)—C(3)	1.525 (5)	1.517 (25)
C(3)—C(4)	1.530 (5)	1.53 (3)
C(4)—S(5)	1.807 (4)	1.848 (19)
S(5)—C(6)	1.803 (4)	1.866 (21)
C(6)—C(7)	1.511 (5)	1.50 (3)
C(7)—C(8)	1.516 (5)	1.524 (25)
C(8)—S(9)	1.815 (4)	1.817 (18)
S(9)—C(10)	1.805 (3)	1.806 (19)
C(10)—C(11)	1.523 (5)	1.52 (3)
C(11)—C(12)	1.520 (5)	1.53 (3)
C(12)—S(13)	1.815 (4)	1.807 (21)
S(13)—C(14)	1.810 (4)	1.774 (19)
C(14)—C(15)	1.518 (5)	1.50 (3)
C(15)—C(16)	1.509 (5)	1.50 (3)
C(2)—S(1)—C(16)	101.62 (17)	101.0 (8)
S(1)—C(2)—C(3)	114.19 (25)	116.1 (12)
C(2)—C(3)—C(4)	112.4 (3)	112.2 (15)
C(3)—C(4)—S(5)	113.8 (3)	112.0 (12)
C(4)—S(5)—C(6)	101.05 (17)	99.9 (9)
S(5)—C(6)—C(7)	110.29 (25)	107.6 (13)
C(6)—C(7)—C(8)	111.3 (3)	109.6 (15)
C(7)—C(8)—S(9)	114.78 (24)	113.6 (12)
C(8)—S(9)—C(10)	101.24 (15)	102.7 (9)
S(9)—C(10)—C(11)	115.08 (23)	114.5 (13)
C(10)—C(11)—C(12)	112.7 (3)	113.1 (15)
C(11)—C(12)—S(13)	114.17 (23)	112.3 (14)
C(12)—S(13)—C(14)	101.03 (16)	100.9 (9)
S(13)—C(14)—C(15)	110.0 (3)	112.0 (13)
C(14)—C(15)—C(16)	112.6 (3)	113.1 (16)
S(1)—C(16)—C(15)	114.0 (3)	118.6 (13)
C(16)—S(1)—C(2)—C(3)	62.1 (3)	65.8 (14)
C(2)—S(1)—C(16)—C(15)	61.5 (3)	64.0 (16)
S(1)—C(2)—C(3)—C(4)	−174.47 (24)	−172.6 (12)
C(2)—C(3)—C(4)—S(5)	69.2 (3)	68.2 (17)
C(3)—C(4)—S(5)—C(6)	74.6 (3)	76.7 (14)
C(4)—S(5)—C(6)—C(7)	−167.59 (25)	−169.7 (13)
S(5)—C(6)—C(7)—C(8)	179.00 (24)	179.7 (12)
C(6)—C(7)—C(8)—S(9)	−177.99 (24)	−178.0 (13)
C(7)—C(8)—S(9)—C(10)	62.9 (3)	60.1 (14)
C(8)—S(9)—C(10)—C(11)	66.6 (3)	61.6 (15)
S(9)—C(10)—C(11)—C(12)	−173.81 (22)	−175.6 (13)
C(10)—C(11)—C(12)—S(13)	66.8 (3)	70.3 (18)
C(11)—C(12)—S(13)—C(14)	75.0 (3)	75.1 (15)
C(12)—S(13)—C(14)—C(15)	−165.59 (25)	−168.0 (14)
S(13)—C(14)—C(15)—C(16)	−178.8 (3)	178.2 (13)
C(14)—C(15)—C(16)—S(1)	178.40 (25)	−178.2 (13)

Table 5. *Fractional atomic coordinates and equivalent isotropic thermal parameters for* α-[16]aneS₄

$$U_{eq} = \tfrac{1}{3}(U_{11} + U_{22} + U_{33}).$$

	x	y	z	U_{eq} (Å²)
S(1)	0.98764 (5)	0.54546 (10)	0.62961 (14)	0.0639 (6)
C(2)	0.92738 (20)	0.4127 (4)	0.7017 (4)	0.0557 (21)
C(3)	0.88124 (17)	0.3387 (4)	0.5844 (4)	0.0521 (19)
C(4)	0.82558 (20)	0.2369 (3)	0.6514 (4)	0.0566 (21)
S(5)	0.74873 (5)	0.31590 (10)	0.75063 (16)	0.0586 (5)
C(6)	0.69187 (20)	0.3783 (4)	0.6001 (4)	0.0574 (22)
C(7)	0.63255 (19)	0.4754 (4)	0.6569 (4)	0.0530 (19)
C(8)	0.58485 (19)	0.5312 (4)	0.5319 (4)	0.0506 (20)
S(9)	0.51380 (5)	0.65376 (10)	0.5877*	0.0563 (5)
C(10)	0.57175 (18)	0.7892 (3)	0.6604 (4)	0.0464 (18)
C(11)	0.62049 (17)	0.8622 (4)	0.5469 (4)	0.0450 (18)
C(12)	0.67412 (18)	0.9644 (3)	0.6165 (4)	0.0507 (19)
S(13)	0.74700 (5)	0.88839 (9)	0.73046 (17)	0.0517 (4)
C(14)	0.80941 (19)	0.8199 (4)	0.5908 (4)	0.0557 (21)
C(15)	0.86440 (19)	0.7203 (4)	0.6604 (4)	0.0595 (22)
C(16)	0.91917 (19)	0.6617 (4)	0.5499 (4)	0.0534 (20)

* Coordinate fixed to define origin.

Table 6. *Fractional atomic coordinates and equivalent isotropic thermal parameters for* β-[16]aneS₄

$$U_{eq} = \tfrac{1}{3}(\Sigma_i \Sigma_j U_{ij} a_i^* a_j^* \mathbf{a}_i.\mathbf{a}_j).$$

	x	y	z	U_{iso}/U_{eq} (Å²)
S(1)	0.7216 (10)	0.1411†	0.01067 (24)	0.063 (4)
C(2)	0.963 (3)	0.0440 (22)	0.0695 (9)	0.050 (5)
C(3)	0.892 (3)	−0.0985 (24)	0.1179 (9)	0.053 (5)
C(4)	1.103 (3)	−0.1588 (25)	0.1736 (9)	0.056 (5)
S(5)	1.1921 (8)	−0.0053 (10)	0.2486 (3)	0.055 (3)
C(6)	0.944 (3)	−0.035 (3)	0.3105 (10)	0.070 (6)
C(7)	0.960 (3)	0.102 (3)	0.3677 (9)	0.052 (5)
C(8)	0.759 (3)	0.0830 (24)	0.4195 (8)	0.047 (5)
S(9)	0.7541 (9)	0.2469 (10)	0.48934 (25)	0.059 (4)
C(10)	0.708 (3)	0.428 (3)	0.4306 (10)	0.055 (5)
C(11)	0.472 (3)	0.4295 (24)	0.3786 (9)	0.051 (5)
C(12)	0.448 (3)	0.579 (3)	0.3253 (10)	0.074 (6)
S(13)	0.6523 (10)	0.5687 (10)	0.2525 (3)	0.063 (3)
C(14)	0.507 (3)	0.4184 (25)	0.1907 (9)	0.055 (5)
C(15)	0.667 (3)	0.360 (3)	0.1327 (9)	0.059 (5)
C(16)	0.551 (3)	0.228 (3)	0.0811 (9)	0.057 (5)

† Coordinate fixed to define origin.

Views of single molecules were generated using the version of *ORTEP* incorporated in the *GX* program system (Mallinson & Muir, 1985), packing diagrams were prepared using *PLUTO* (Motherwell, 1976) and molecular-geometry calculations utilized *CALC* (Gould & Taylor, 1985). Experimental details are given in Table 1.*

Molecular geometry and atomic coordinates are given in Tables 4–6.

γ *form*

This form appears to crystallize in the orthorhombic space group *Fdd*2, with $a = 18.0183$ (15), $b = 21.338$ (3), $c = 24.145$ (3) Å, $V = 9283$ Å³. This would imply $Z = 24$ and that at least some of the molecules lie on crystallographic twofold axes. How-

of 0.0873 and 0.1150: the other gave values of 0.0787 and 0.0942 and was accordingly adopted.

The program used to solve both structures was *SHELXS86* (Sheldrick, 1986) and the program used to refine the structures was *SHELX76* (Sheldrick, 1976). Refinement was by full-matrix least squares.

ever, analysis of reflection profiles prior to data collection and the persistent failure of the structure to solve indicated that the crystals were badly affected by twinning and no structural information could be obtained.

Results and discussion

Crystals of three forms of [16]aneS₄ – acicular (α), lamellar (β) and columnar (γ) – were obtained by solvent diffusion of hexane into solutions of the compound in CH_2Cl_2: the α and β forms were obtained as a mixture at ambient temperature while the γ form was grown at 243 K. In order to confirm the existence of the three different crystalline forms of [16]aneS₄, melting points and mixed melting points were determined for the three types of crystal (see Table 2). The melting point of each mixture was lower than those of its pure components, confirming that each morphology corresponded to a distinct crystalline phase. However, the changes observed were small, implying that the intermolecular forces, and therefore the crystal packing, were similar in all three polymorphs.

Single-crystal X-ray structural determinations were undertaken on all three forms of [16]aneS₄. Although the structures of the α and β forms were

readily solved, it was not possible to solve the structure of the γ form with the data available. The conformations of [16]aneS₄ in the α and β forms are essentially the same and are shown in Fig. 1. The molecule adopts a [3535] rectangular conformation (Fig. 4) with local twofold symmetry. Two S atoms lie at opposite corners of the ring in *exo* positions with the other two occupying sites along the longer side of the rectangle. The transannular S⋯S distances of 5.626 (2) Å (α form) and 5.550 (9) Å (β form) rule out any charge-transfer interactions of the type observed in several 1,5-dithiocane derivatives (Adamowicz, Broeker & Glass, 1991). Six of the eight C—S bonds, but only two of the eight C—C bonds, have *gauche* placements. This is significant given the known tendency of thioether macrocycles to maximize the number of *gauche* C—S torsions (*vide supra*) (Cooper, Foxman, Hartman, Storey & Wolf, 1987). However, since all the S atoms in [16]aneS₄ are separated by three —CH₂— groups, destabilizing S⋯S interactions should be much weaker than in [12]aneS₄ and [14]aneS₄, which both contain S atoms separated by only two —CH₂— groups. Clearly, S⋯S repulsions are no longer suffi-ciently large to impose an all-*exo*dentate conforma-
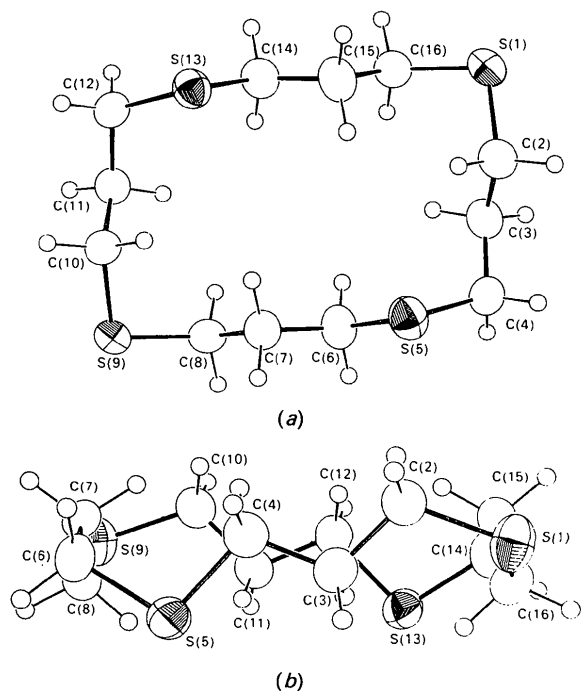

(a)

(b)

Fig. 1. (a), (b) Two views of the structure of the α form of [16]aneS₄ with the atom-numbering scheme adopted. Thermal ellipsoids are drawn at the 50% probability level, except those of H which have arbitrary radii of 0.10 Å for clarity. The numbering scheme in the β form is the same, and the conformation barely distinguishable.
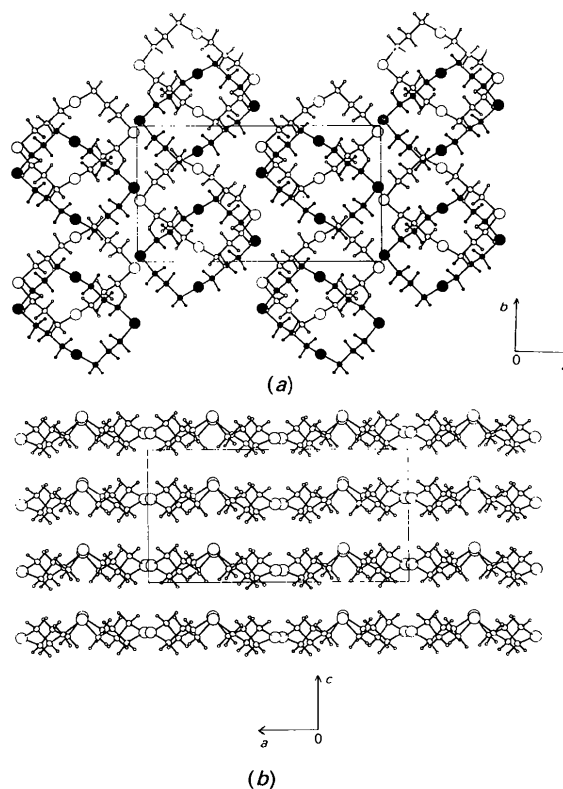

(a)

(b)

Fig. 2. Packing diagrams for the α form of [16]aneS₄ showing (a) the relative orientations of the molecules, with those in one layer shaded for clarity, and (b) the stacking of layers of molecules perpendicular to c.

tion on the [16]aneS$_4$ macrocycle. This effect has been observed previously for the exclusively —(CH$_2$)$_3$— linked [12]aneS$_3$ macrocycle, which adopts a square conformation with only four *gauche* C—S bonds (Admans, Cooper & Rawle, 1988). A preliminary refinement of a badly disordered single-crystal structure implied that [16]aneSe$_4$, the tetra-selena analogue of [16]aneS$_4$, adopts a rectangular [3535] conformation in the solid state (Batchelor, Einstein, Gay, Gu, Johnston & Pinto, 1989).

The crystal packing in the α and β polymorphs is shown in Figs. 2 and 3. The [16]aneS$_4$ molecules are approximately planar rectangles, with a central cleft. The packing of the α form is dominated by layers of
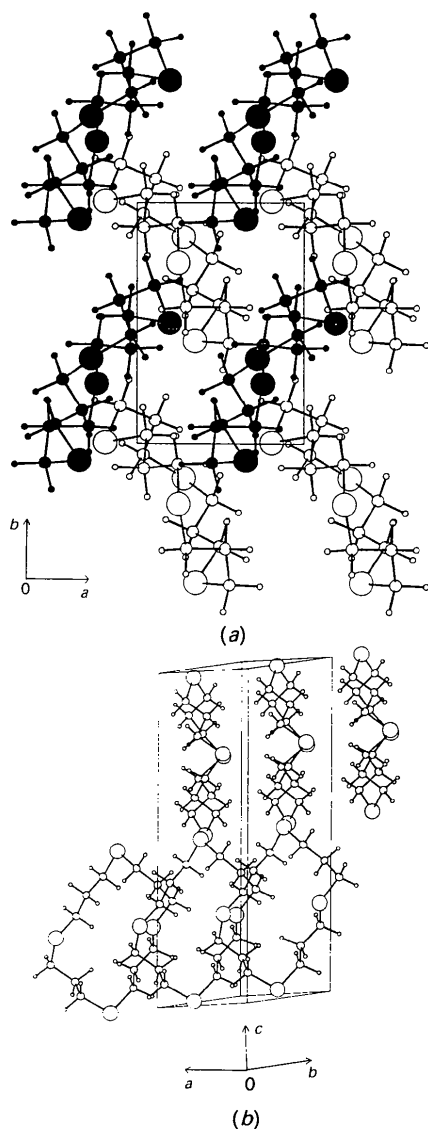

(a)

(b)

Fig. 3. Packing diagrams for the β form of [16]aneS$_4$, where alternate rows of molecules, related by the 2$_1$ screw axis, are seen in (a) plan and (b) elevation, the latter viewed along [110].

molecules parallel to (001), each being related to the next by the 2$_1$ screw axes. These layers are shown in plan (Fig. 2a) and in elevation (Fig. 2b). In the plan view, the dominant features are columns parallel to (001) which in turn are grouped into discrete bilayers parallel to [010]. In the β form, the packing may be described as a folding of the layers in the α form. This packing is less efficient, as shown by the lower calculated density and melting point of the β form. Fig. 3(b) shows a projection along [110], where alternate rows of molecules, related by the 2$_1$ screw axis, are seen in plan: Fig. 3(a) shows the rows in elevation.

The structures of the metal-free 12- and 14-membered tetraoxa and tetrathia crown ethers are related to the conformations preferred by their parent hydrocarbons. Both [12]aneO$_4$ (Groth, 1978a) and [12]aneS$_4$ (Robinson & Sangokoya, 1988; Cooper, Foxman, Hartman, Storey & Wolf, 1987) adopt square {[3333] in Dale's notation (Dale, 1963)} conformations in the solid state, which is also the form observed in the crystal structure of C$_{12}$H$_{24}$ (Dunitz & Shearer, 1960). The structures of [12]aneS$_4$ and [12]aneO$_4$ differ, however, in the positioning of the heteroatoms within the square ring. In [12]aneO$_4$ the O atoms lie along the sides of the square ring giving four *anti* and four *gauche* C—O torsions, whilst in [12]aneS$_4$ the S atoms lie at the corners of the ring with all eight C—S bonds adopting *gauche* placements. This reflects the different 1,4-interactions in *gauche* X—C—C—X and C—C—X—C fragments (X = O, S) (Cooper, Foxman, Hartman, Storey & Wolf, 1987). The structures of [14]aneO$_4$ (Groth, 1978b), [14]aneS$_4$ (DeSimone & Glick, 1976) and [16]aneO$_4$ (Groth, 1971, 1974) exhibit similar features to those above. The tetraprotonated {[14]aneN$_4$H$_4$}$^{4+}$ macrocycle also adopts a rectangular conformation in the solid state (Blake, Greig & Schröder, 1990) while the saturated tetraaza rings [14]aneN$_4$ (Curtis, 1979) and [16]aneN$_4$ (Ekstrand, Raymond & Smith, 1978) show *endo*dentate conformations, similar to those observed in tetragonal metal complexes of these ligands. However, in these aza structures internal hydrogen bonding plays an important and perhaps overriding role.

Molecular mechanics calculations

In order to quantify the conformational flexibility of [16]aneS$_4$, and to explain its adoption of a [3535] conformation in the solid state, molecular mechanics calculations were performed on selected conformers of this molecule (Grant, Setzer, Tang & VanDerveer, 1991) and of C$_{16}$H$_{32}$. The conformations chosen for study (Fig. 4) were those proposed in Dale's pseudo-rotation mechanism for 16-membered rings and those observed in complexes of [16]aneS$_4$. The calcu-

lations were performed using the MM2(87) force field (Allinger & Yuh, 1987) and initial model structures were taken from crystal structure coordinates or prepared using the *MINP* input generation program (Allinger & Lii, 1987). The results of the calculations for the range of conformers defined above are listed in Table 3. The strain energies calculated for $C_{16}H_{32}$ are in agreement with those reported previously (Allinger, Gorden & Profeta, 1980).

According to the molecular mechanics calculations the lowest strain energy conformer for both [16]aneS₄ and $C_{16}H_{32}$ is a square [4444] form; for [16]aneS₄, this is the [4444] ring with S atoms occupying corner positions, the conformer with the maximum number of *gauche* C—S torsions, and it is preferred over other [4444] conformers by 0.7–0.8 kcal mol⁻¹. However, the [3535] conformation is significantly stabilized for [16]aneS₄ compared to $C_{16}H_{32}$, so that this conformer lies only 0.7 kcal mol⁻¹ above the [4444] conformer *A*. This is due to the reduction in the number of unfavourable van der Waals interactions between H atoms on adjacent sides of the ring on replacing four CH_2 groups in $C_{16}H_{32}$ by S atoms in [16]aneS₄. Other conformers are also stabilized for [16]aneS₄ over their $C_{16}H_{32}$ analogues for the same reason. The two *endo* conformations of [16]aneS₄ examined lay over 6 kcal mol⁻¹ above the other forms, and it is unlikely that these would be significantly populated in the absence of a metal ion (Hancock, 1989).

The conformational structure of cyclohexadecane, $C_{16}H_{32}$, is still the subject of some controversy. Early IR (Borgen & Dale, 1970), NMR (Anet & Cheung, 1975) and molecular mechanics studies (Allinger, Gorden & Profeta, 1980) implied that this molecule adopts a square [4444] conformation at low temperatures, with a rectangular [3535] isomer lying 1.2–3.5 kcal mol⁻¹ higher in energy being populated at higher temperatures. A pseudorotation mechanism for the interconversion of these forms was proposed by Dale (Dale, 1976), and the barrier to pseudorotation was measured as 6.7 ± 0.2 kcal mol⁻¹ (Anet & Cheung, 1975). However, a more recent analysis of the IR and Raman spectra of crystalline and liquid $C_{16}H_{32}$ has thrown considerable doubt on these results, with the C_{16} ring being rather more flexible than expected from the earlier studies (Elliger, Mattice, Shannon, Snyder & Strauss, 1989; Ferguson, Glauser & Raber, 1989). Molecular mechanics calculations did not successfully reproduce the increased flexibility seen in these new measurements, and so the interpretation of MM2 calculations on heterocycles such as [16]aneS₄ should be treated with caution.

In conclusion, it has been shown that [16]aneS₄ adopts a rectangular [3535] conformation in the solid state. Molecular mechanics calculations suggest that this is probably not the minimum energy conformer, the ground state being a [4444] conformation with S atoms occupying the corners of the square ring. However, the energy differences involved are very
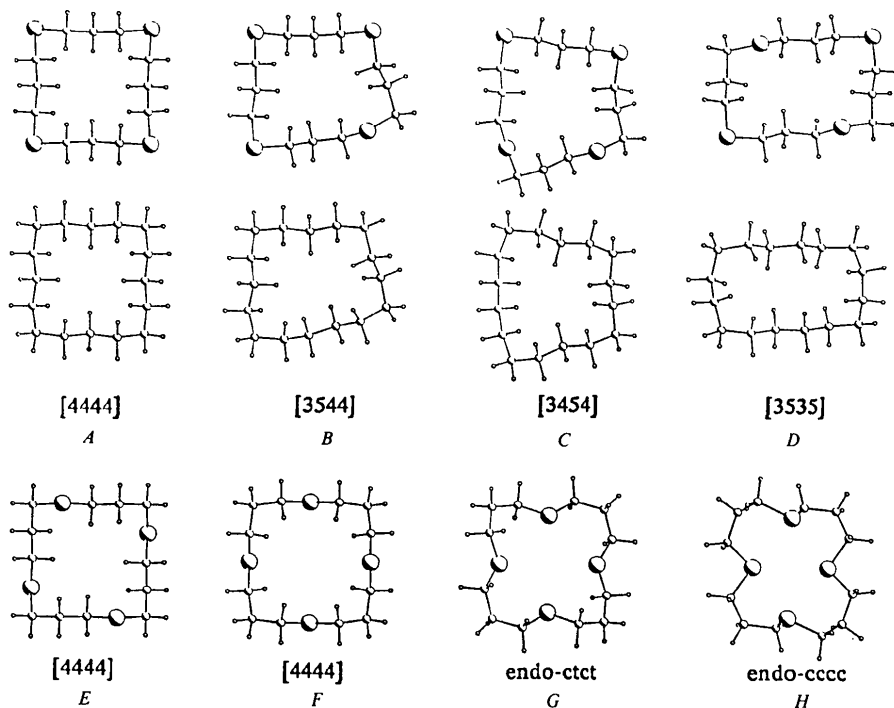

[4444]
A

[3544]
B

[3454]
C

[3535]
D

[4444]
E

[4444]
F

endo-ctct
G

endo-cccc
H

Fig. 4. Conformers of [16]aneS₄ and $C_{16}H_{32}$ studied using MM2 calculations.

small, so that other forms are likely to be significantly populated at room temperature. The observation of [3535] conformations in the solid-state structures of [16]aneS$_4$ may, in any case, be attributed to crystal packing forces rather than to any inherent conformational stability. It should be noted that molecular mechanics energy calculations on medium ring cycloalkanes (Elliger, Mattice, Shannon, Snyder & Strauss, 1989; Ferguson, Glauser & Raber, 1989) have also shown that several conformations have energies very close to the minimum, so that one preferred conformation is not reliably identified.

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