DALTON

Preorganization of tetrathiamacrocyclic ligands: implications from computed and experimentally determined structures‡

Peter Comba,*,† Andreas Fath, Andreas Kühner and Bernd Nuber

Anorganisch-Chemisches Institut, Universität Heidelberg, Im Neuenheimer Feld 270, 69120 Heidelberg, Germany

The tetrathiamacrocycles *trans*-6,13-dihydroxy-1,4,8,11-tetrathiacyclotetradecane (L^1) and its benzo- (L^2), *syn*- and *anti*-dibenzo-substituted derivatives (L^3 and $L^{3'}$, respectively) have been prepared by conventional methods, and a benzo-substituted-1,4,7,10-tetrathiacyclotridecane (L^4) was obtained by substitution of *o*-dichlorobenzene after activation with an organometallic fragment. The structures of L^1–L^4 and of the four palladium(II) complexes $[PdL^1]Cl_2\cdot 2H_2O$, $[PdL^2][PF_6]_2$, $[PdL^{3'}][PF_6]Cl$ and $[PdL^4][PF_6]_2$ were determined by X-ray crystallography. All the experimentally determined structures were accurately reproduced by molecular mechanics calculations, using a constant-parametrization scheme. Two parameters for the evaluation of the extent of preorganization of free macrocycle molecules, based on structural and strain-energy differences of the free macrocycles and their corresponding metal complexes, are introduced and discussed on the basis of the experimentally determined and computed structural data for L^1–L^4, their metal complexes and other similar ligand and metal complex systems. The implications for the design of new compounds leading to high stability and high metal-ion selectivity are outlined.

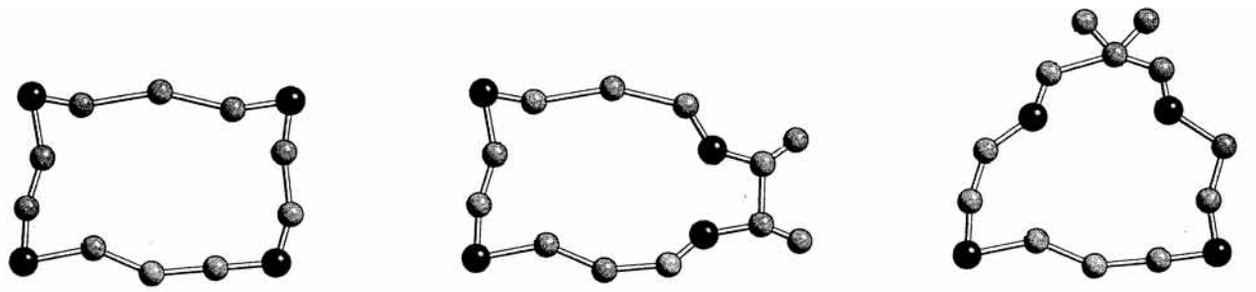
Macrocyclic ligand systems and their co-ordination to transition-metal centres are a focal point when enhanced stability or metal-ion selectivity are of importance. Applications include metal-ion analysis, recycling and refinement, detoxification of aqueous solutions and various medicinal applications, such as diagnosis and therapy of tumours. Fundamental reasons for enhanced complex stabilities and for large stability differences (metal-ion selectivities) have been widely discussed on the basis of both experimental data[1,2] and theoretical methods.[3] The macrocyclic effect[1] and ligand preorganization[3,4] are referred to as the two basic, partly related, effects responsible for high stability and selectivity. Since these are related to the structure of the free macrocycle and that of the metal complexes, *i.e.* to the strain imposed by the metal on the ligand and the strain imposed by the ligand on the metal centre, molecular mechanics was long believed to be an ideal tool to predict relative stabilities and selectivities. There are a number of reasons why, so far, this hope is largely unfulfilled.[3d] Interpretations of molecular mechanics calculations in this area, including studies on thermodynamic[3,5] and on kinetic aspects,[6] are usually restricted by approximations and neglections, and there are possibilities for oversimplifications and misinterpretations which might unnecessarily discourage use of molecular mechanics in this field.

Our aim was to develop a simple and reliable technique which would allow interpretation and evaluation of the extent of preorganization of a given ligand system with respect to a specific metal ion. We are aware that in the original definition[4] a preorganized system was, by necessity, a relatively rigid system, the structure of which was close to that adopted on complex formation. In contrast, the present work deals with quite flexible systems. Tetrathiamacrocycles were chosen for testing our approach, because these are known to prefer, in contrast to the corresponding oxa and aza systems, exodentate conformations.[7] Substitution of the ligand backbone is known to lead in some cases to an increase in preorganization, *i.e.* to ligand conformations with one or several sulfur atoms in an endodentate geometry (see Scheme 1). Reinforced macrocyclic ligands in general are widely used to enhance metal complex stability and metal-ion selectivity.[3b,8] With tetrathiamacrocyclic ligand systems, cyclohexyl, phenyl and methyl substituents have, among others, been used to stabilize endodentate conformations.[9] However, the results published so far, including structural, computational, electrochemical, thermodynamic and kinetic data, do not allow one to assess the preorganization, *i.e.* the structural effects, systematically.

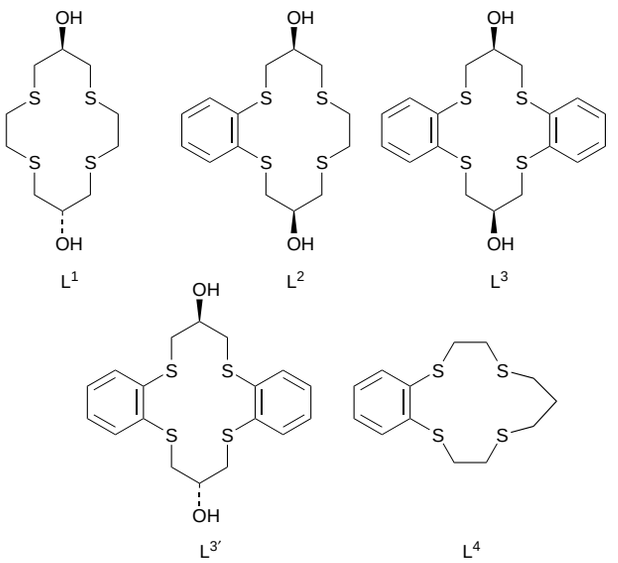
We have used both benzo- and hydroxy-substituted macrocyclic thioethers to try to stabilize endodentate conformations. Hydroxy rather than methyl substituents were used to increase the water solubility of the compounds [the hydroxy-substituted compounds and their palladium(II) complexes have, in contrast to the purely benzo-substituted species, been handled in aqueous solution, see Experimental section]. Benzo-substituted rings were studied since the preorganizational effects of benzo substituents are controversial. Palladium(II) compounds were of interest because their enforced rigid square-planar geometry leads to maximum structural and strain-energy differences in comparison with the endodentate (and also with partially preorganized) metal-free conformations. Also, from the 32 known crystal structural analyses of tetrathiamacrocyclic ligands, eight were of metal free and six of nickel-group metal complexes. The eight structures presented here complete this set to give a useful basis for strucural correlations within the nickel group. The inertness of these complexes does not allow, however, the experimental determination of thermodynamic data for comparison. This was not the aim of the present, purely structural analysis. The effects of ligand preorganization upon metal-ion stability are well documented elsewhere.[1–4] It should be noted that the usual neglect of environmental effects in molecular mechanics calculations (solvation, ion pairing), that of entropy effects (including the effects of temperature on equilibria) and electronic effects (the preference of metal ions for specific donor groups) are less important in a purely structural analysis. We also stress that, in contrast to the original definition of ligand preorganization,[4] we analyse the extent of preorganization as a continuum involving partially and fully preorganized systems. Also, ligand preorganization clearly is a metal-ion-specific property.

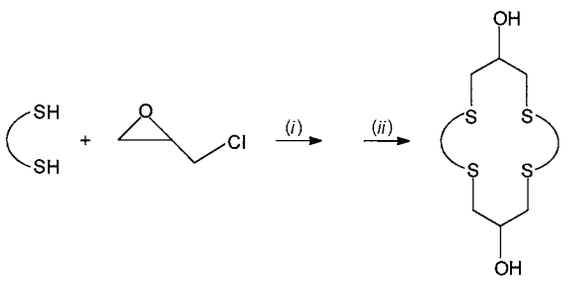
† E-Mail: comba@akcomba.oci.uni-heidelberg.de

‡ *Non-SI unit employed*: dyn = 10^{-5} N.

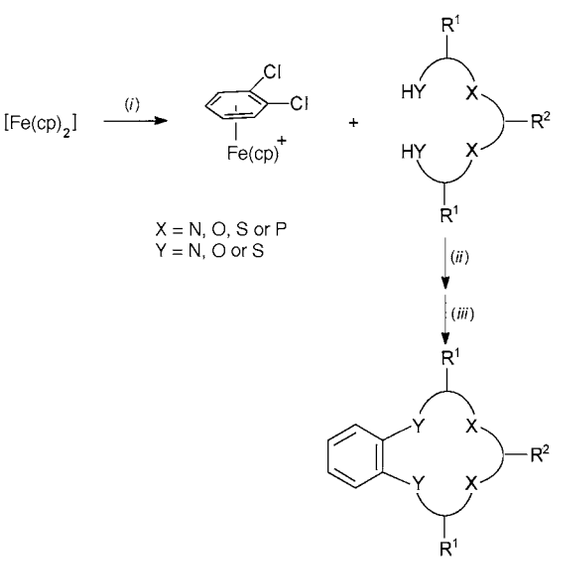


Scheme 1 The effect of geminal and vicinal substituents on the conformation of thiamacrocycles





Scheme 2 Synthesis of tetrathioether macrocycles, conventional route: (*i*) NEt_3, absolute EtOH, room temperature (r.t.), 24 h; (*ii*) Cs_2CO_3, dithiole, absolute dimethylformamide (dmf), 100 °C, 24 h, high dilution



Scheme 3 General scheme for cyclization *via* a transition-metal-activated, aromatic S_N reaction. (*i*) Al, $AlCl_3$, in *o*-dichlorobenzene, 150 °C, 6 h; (*ii*) dithiaalkanedithiol, K_2CO_3, absolute tetrahydrofuran (thf), 50 °C, 24 h; (*iii*) O_2, cp = η^5-C_5H_5

Results and Discussion

Macrocycle syntheses

Two different methods were used to prepare the macrocycles. A conventional route,[10] involving high dilution techniques and the presence of Cs_2CO_3, was used for L^1–L^3 and $L^{3'}$ (Scheme 2). For L^4 we have adopted a novel approach. The co-ordination of a cyclopentadienyliron fragment to *o*-dichlorobenzene leads to its activation for a nucleophilic substitution reaction (Scheme 3). Similar methods have been used for aromatic substitution reactions involving aliphatic and aromatic amines, alcohols, thiols and carbanions.[11–13] The dichloroarene sandwich compound is easily accessible *via* reductive ligand exchange on ferrocene.[14] In presence of oxygen, cyclization with a suitable dithiole is followed by immediate decomplexation. This approach has the potential to yield new macrocyclic systems that are not easily accessible by conventional methods. These include compounds with variable ring size, with more than two benzo substituents, and with donors other than sulfur.

Crystal structures

Schakal[15] plots of the structurally characterized macrocycles and complexes are shown in Fig. 1, which also defines the atom numbering for Tables 1–4. Details of the data collection and refinement are given in Table 7. Bond lengths and valence angles for the macrocycles and the corresponding palladium(II) complexes are presented in Tables 1 and 2. Table 3 summarizes the torsion angle data. Structural data for 1,4,8,11-tetrathiacyclotetradecane ([14]aneS$_4$, L^0) and its nickel(II) complex [16*a*,17*a*,*b*] are included for comparison. All structural data are as expected from published data on similar systems.[16*b*,18]

L^1. The crystal structure defines L^1 with approximately exodentate conformation. The molecule has the crystallographically required inversion centre. The two hydroxo substituents are in *anti* position, forming hydrogen bridges to the neighbouring molecules. In contrast to the unsubstituted ligand L^0, where the four sulfur atoms are at the corners of an approximately rectangular molecule (see Scheme 1), only two donors are fully exodentate. Compound L^1 approximately keeps a rectangular geometry, but the corner positions are occupied by two sulfur atoms [S(4), S(11)] and two carbon atoms [C(7), C(14)]. This conformational difference between the unsubstituted macrocycles L^0 and L^1 also emerges from a comparison of the torsion angles φ (see Table 3). In the unsubstituted macrocycle L^0 [ref. 16(*a*)] both SC–CS and all SC–CC bonds have an *anti* orientation (φ ≈ 180), and all CS–CC conformations are *gauche* (φ ≈ 60). In the substituted ring L^1 two of the four SC–CC torsions, *i.e.* the ones involving the substituent SC–C(OH)C, are *gauche* and two of the eight CS–CC bonds are *anti*. This variation reflects the compromise between minimizing repul-

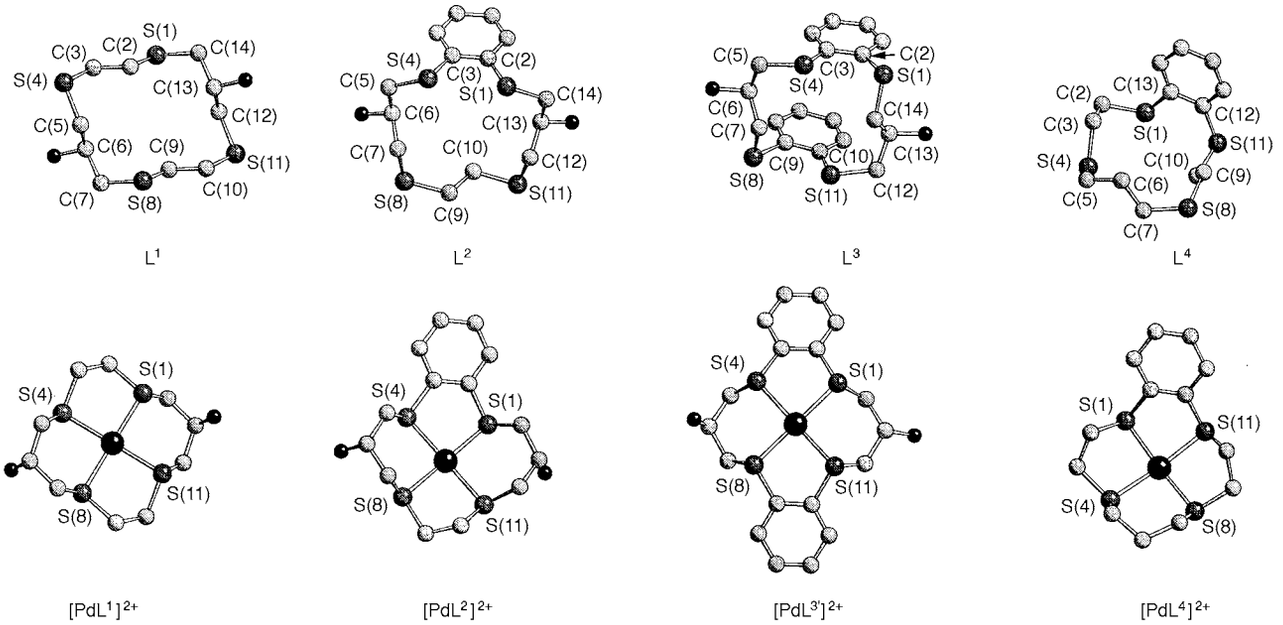


Fig. 1 SCHAKAL[15] plots of the experimentally determined structures

Table 1 Bond lengths (Å) of the organic backbone of the tetrathiamacrocycles and of their palladium(II) complexes[a]

	L^0	$[NiL^0]^{2+}$	L^1	$[PdL^1]^{2+}$	L^2	$[PdL^2]^{2+}$	L^3	$[PdL^{3'}]^{2+}$	L^4	$[PdL^4]^{2+}$
S(1)–C(2)	1.817(3)	1.808(5)	1.814(2)	1.832(3)	1.755(6)	1.780(5)	1.762(8)	1.783(3)	1.800(5)	1.842(10)
C(2)–C(3)	1.504(4)	1.489(8)	1.521(3)	1.506(5)	1.395(7)	1.385(7)	1.410(11)	1.385(5)	1.507(7)	1.512(14)
C(3)–S(4)	1.803(3)	1.821(6)	1.803(2)	1.833(3)	1.777(5)	1.792(5)	1.743(8)	1.784(3)	1.808(5)	1.796(10)
S(4)–C(5)	1.802(3)	1.804(6)	1.809(3)	1.816(3)	1.795(5)	1.840(6)	1.812(7)	1.823(3)	1.791(5)	1.796(10)
C(5)–C(6)	1.505(3)	1.502(8)	1.522(4)	1.527(4)	1.531(7)	1.519(8)	1.527(10)	1.513(5)	1.524(6)	1.565(13)
C(6)–C(7)	1.518(3)	1.519(8)	1.530(4)	1.532(4)	1.496(7)	1.523(8)	1.506(10)	1.524(5)	1.514(6)	1.565(13)
C(7)–S(8)	1.812(3)	1.800(5)	1.807(2)	1.808(3)	1.813(5)	1.803(5)	1.808(7)	1.810(3)	1.806(4)	1.796(10)
S(8)–C(9)					1.825(6)	1.808(5)	1.754(7)	1.780(3)	1.800(5)	1.796(10)
C(9)–C(10)					1.468(8)	1.484(7)	1.415(10)	1.381(4)	1.496(7)	1.491(14)
C(10)–S(11)					1.818(6)	1.840(6)	1.753(7)	1.780(3)	1.814(5)	1.842(10)
S(11)–C(12)					1.789(6)	1.814(5)	1.815(7)	1.824(3)	1.764(5)	1.753(9)
C(12)–C(13)					1.513(8)	1.523(8)	1.520(10)	1.519(4)	1.394(5)	1.387(18)
C(13)–C(14)					1.524(8)	1.520(7)	1.515(9)	1.523(4)	*b*	*b*
C(14)–S(1)					1.810(5)	1.816(4)	1.803(8)	1.814(3)	1.763(6)	1.753(9)

[a] The data for L^0 and $[NiL^0][BF_4]_2$ are from refs. 16(*a*), 17(*a*) and 17(*b*). [b] L^4 is a 13-membered ring in which C(13)–C(14) does not exist; C(13)–S(1) is tabulated instead of C(14)–S(1).

sion involving the hydroxy substituents and the inherent constraints of a 14-membered S_4 macrocycle.

L^2. The experimentally determined conformation of L^2 is half *endo*/half *exo*. The two hydroxy substituents are disposed to the same side of the plane defined by the four donor atoms (*syn* configuration), and to the same side as the benzo substituent. These groups and the phenyl fragment enforce displacement of the attached sulfur atoms toward the macrocyclic ring centre, so that the adjacent carbon atoms now occupy the corner positions of the approximately rectangular geometry. Owing to the two sp^2 carbon atoms in the macrocycle, the torsion angles change significantly (see Table 3). From a comparison of L^2 with L^1 and structural data for other S_4 macrocycles it seems that a phenyl spacer has a stronger preorganizational influence than hydroxy substituents. This is possibly due to the fact that the hydroxy substituents are only influencing the orientation of one of the two adjacent sulfur donors in the fourteen-membered macrocycle (see L^1; with geminal substitution the two neighbouring donors are preorganized to some extent), while the two α substituents of a phenyl group have a fixed orientation.

L^3. The macrocycle L^3 is found in a conformation best described as approximately exodentate. It has structural features similar to those of L^1. This also emerges from the torsion angle data (see Table 3). The two phenyl rings and the hydroxy groups are all on the same side of the best plane through the donor atoms. The phenyl rings are roughly parallel to each other, with a distance of 4.3–4.4 Å between the two planes. In the elementary cell there are two different molecules (ratio 1:1). The species not discussed here is an oxidation product, with one sulfur atom oxidized to a sulfoxide (L^{30}, Table 7).

L^4. The molecule is a 13-membered ring without hydroxy substituents. It is formally derived from the unsubstituted 14-membered macrocycle L^0 by substitution of a propylene bridge with an *o*-phenylene bridge. The phenylene fragment is approximately perpendicular to the best plane through the donor atoms. Three of the four sulfur atoms are half exo-, half endo-dentate while the fourth is fully exodentate.

$[PdL^1]Cl_2\cdot 2H_2O$. Co-ordination of L^2 to palladium(II) leads to an enforced endodentate conformation of the macrocycle. The overall co-ordination geometry is square planar with Pd–S *ca.* 2.29 Å and S–Pd–S *ca.* 90°. The two hydroxy substituents are on opposite sides of the macrocyclic plane (*anti* configuration) and in axial positions of the six-membered chelate rings which have chair conformations. This geometry is possibly enforced by packing effects or hydrogen bonds. The

Table 2 Valence angles (°) of the organic backbone of the tetrathiamacrocycles and their palladium(II) complexes

	L^0	$[NiL^0]^{2+}$	L^1	$[PdL^1]^{2+}$	L^2	$[PdL^2]^{2+}$	L^3	$[PdL^{3'}]^{2+}$	L^4	$[PdL^4]^{2+}$
S(1)–C(2)–C(3)	113.4(2)	106.8(2)	108.4(1)	108.4(2)	118.5(4)	120.7(4)	120.9(6)	120.8(2)	113.8(3)	105.3(7)
C(2)–C(3)–S(4)	114.1(2)	106.2(2)	114.4(1)	108.0(2)	118.3(4)	120.1(5)	118.4(5)	119.9(2)	111.1(3)	115.8(7)
C(3)–S(4)–C(5)	103.6(1)	102.8(3)	102.5(1)	102.8(1)	103.3(3)	99.3(2)	104.6(3)	101.3(2)	99.9(2)	101.1(5)
S(4)–C(5)–C(6)	115.1(2)	110.6(4)	115.5(2)	111.0(2)	114.3(3)	114.6(4)	115.9(5)	110.6(2)	114.7(3)	112.7(8)
C(5)–C(6)–C(7)	111.6(2)	115.0(4)	111.4(2)	116.0(2)	110.2(4)	115.7(5)	112.4(5)	113.8(2)	112.3(4)	114.8(11)
C(6)–C(7)–S(8)	114.1(2)	111.5(3)	115.7(2)	112.2(2)	113.7(4)	111.3(4)	115.8(4)	110.0(2)	114.7(3)	112.7(8)
C(7)–S(8)–C(9)	102.2(1)	102.6(2)	101.8(1)	102.3(1)	102.1(3)	103.5(3)	101.6(3)	102.0(1)	102.7(2)	101.1(5)
S(8)–C(9)–C(10)					112.8(4)	114.1(4)	123.9(6)	120.2(2)	113.3(3)	115.8(7)
C(9)–C(10)–S(11)					112.7(4)	107.7(4)	116.3(5)	120.0(2)	113.8(3)	105.3(7)
C(10)–S(11)–C(12)					101.0(3)	99.4(2)	105.6(4)	102.6(2)	100.2(2)	105.2(4)
S(11)–C(12)–C(13)					114.2(4)	112.1(5)	116.6(5)	110.2(2)	121.8(3)	120.2(3)
C(12)–C(13)–C(14)					110.6(5)	113.6(4)	113.8(5)	113.0(2)	*	*
C(13)–C(14)–S(1)					113.1(4)	111.3(4)	113.5(5)	110.6(2)	117.9(3)*	120.2(3)*
C(14)–S(1)–C(2)					103.2(3)	101.3(2)	100.4(4)	101.3(4)	103.4(2)*	105.2(4)*

* L^4 is a 13-membered ring in which C(12)–C(13)–C(14) does not exist; C(12)–C(13)–S(1) and C(13)–S(1)–C(2) are tabulated instead of C(13)–C(14)–S(1) and C(14)–S(1)–C(2).

Table 3 Torsion angles (°) of the organic backbone of the tetrathiamacrocycles and their palladium(II) complexes

	L^0	$[NiL^0]^{2+}$	L^1	$[PdL^1]^{2+}$	L^2	$[PdL^2]^{2+}$	L^3	$[PdL^{3'}]^{2+}$	L^4	$[PdL^4]^{2+}$
S(1)–C(2)–C(3)–S(4)	−176	−61	175	65	3	3	−4	0	−73	57
C(2)–C(3)–S(4)–C(5)	−60	159	−58	−154	−150	122	−163	125	169	82
C(3)–S(4)–C(5)–C(6)	−62	−175	−54	174	70	−169	65	−176	−78	−174
S(4)–C(5)–C(6)–C(7)	178	71	178	−74	71	69	60	81	−72	77
C(5)–C(6)–C(7)–S(8)	177	−72	−63	74	−176	−75	−172	−79	167	−77
C(6)–C(7)–S(8)–C(9)	63	178	−69	−173	112	−178	62	175	−68	174
C(7)–S(8)–C(9)–C(10)	67	−57	−177	154	−89	−80	77	124	−54	−82
S(8)–C(9)–C(10)–S(11)					−177	−55	1	−3	−171	−57
C(9)–C(10)–S(11)–C(12)					−92	164	−167	129	−54	161
C(10)–S(11)–C(12)–C(13)					−84	−166	69	−175	−81	−125
S(11)–C(12)–C(13)–C(14)					172	78	53	79	−2[a]	0[a]
C(12)–C(13)–C(14)–S(1)					−73	−81	−170	−81	*b*	*b*
C(13)–C(14)–S(1)–C(2)					−69	174	68	175	150[b]	125[b]
C(14)–S(1)–C(2)–C(3)					152	−130	79	−125	−66[b]	−161[b]

[a] Torsion angle S(4)–C(12)–C(13)–S(1) is tabulated instead of S(4)–C(12)–C(13)–C(14). [b] L^4 is a 13-membered ring in which C(12)–C(13)–C(14)–S(1) does not exist; C(12)–C(13)–S(1)–C(2) and C(13)–S(1)–C(2)–C(3) is tabulated instead of C(13)–C(14)–S(1)–C(2) and C(14)–S(1)–C(2)–C(3).

Table 4 Bond lengths (Å) and valence angles (°) of the chromophores of $[PdL^1]Cl_2 \cdot 2H_2O$, $[PdL^2][PF_6]_2$, $[PdL^{3'}][PF_6]Cl$ and $[PdL^4][PF_6]_2$

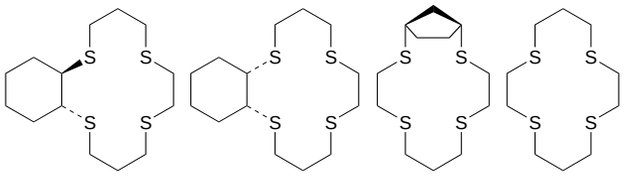
	$[PdL^1]^{2+}$	$[PdL^2]^{2+}$	$[PdL^{3'}]^{2+}$	$[PdL^4]^{2+}$
Pd–S(1)	2.289(1)	2.278(2)	2.288(1)	2.279(3)
Pd–S(4)	2.291(1)	2.297(2)	2.293(1)	2.283(3)
Pd–S(8)	2.289(1)	2.294(2)	2.289(1)	2.283(3)
Pd–S(11)	2.291(1)	2.301(2)	2.283(1)	2.279(3)
S(1)–Pd–S(4)	90.3(1)	88.6(1)	88.08(3)	88.9(1)
S(4)–Pd–S(8)	89.7(1)	90.0(1)	91.81(3)	93.8(1)
S(8)–Pd–S(11)	90.3(1)	88.1(1)	87.76(3)	88.9(1)
S(11)–Pd–S(1)	89.7(1)	93.4(0)	92.21(3)	87.4(1)
S(1)–Pd–S(8)	180	177.9(1)	176.36(3)	171.6(1)
S(4)–Pd–S(11)	180	176.5(1)	177.75(3)	171.6(1)

configuration with respect to the sulfur donors is *SSSS*. The fact that the four donor atoms have the same configuration leads to the two six-membered chelate rings lying on opposite sides of the macrocyclic plane, *i.e.* in *anti* configuration. The five-membered chelate rings adopt a λδ conformation. The geometries of the chromophores of the palladium(II) complexes are given in Table 4.

$[PdL^2][PF_6]_2$. The overall co-ordination geometry is square planar with Pd–S *ca.* 2.3 Å and S–Pd–S *ca.* 90°. In terms of the chromophore there is no significant difference between aliphatic thioether donors and those attached directly to the phenyl ring (see Tables 1, 2 and 4). The two hydroxy substituents are on the same side of the macrocyclic plane (*syn* configuration) and in equatorial positions of the six-membered chelate rings which have chair conformations. The configuration with respect to the sulfur donors is *SRRS*, *i.e.* the two donors of each of the six-membered chelate rings have the same configuration, but it is different within each of the two five-membered chelate rings. This leads to the two six-membered chelate rings lying on the same side of the macrocyclic plane, *i.e.* in *syn* configuration. The five-membered chelate ring bearing the phenyl group adopts an envelope conformation and the other five-membered ring adopts a λ conformation.

$[PdL^{3'}][PF_6]Cl$. The co-ordination geometry is close to ideal square planar (see Table 4). The five-membered chelate rings bearing the phenyl groups adopt an envelope conformation and the two planes of the phenyl rings are considerably twisted out of the PdS_4 plane (21°), both toward the same side of the chromophore. The six-membered chelate rings are found in a chair conformation, directed to the same side of the *SRRS*-configurated PdS_4 plane, and to the same side as the phenylene substituents. The hydroxy substituents are *anti* to each other, one in an equatorial and the other in an axial orientation.

$[PdL^4][PF_6]_2$. The structural features of the $[PdL^4]^{2+}$ cation are similar to those of $[PdL^2]^{2+}$ and $[PdL^{3'}]^{2+}$ (see Tables 1, 2 and 4). The configuration with respect to the sulfur donors is *SRRS*. The reduction of the macrocyclic ring size from 14- to 13-membered leads to a small but significant decrease in the Pd–S distances from *ca.* 2.29 to 2.28 Å. The bite angles of the five-membered chelate rings are a little smaller than required for a square-planar geometry (*ca.* 88°), while those of the six-membered chelate rings are, as usual, a little larger (*ca.* 93°). This leads to a slightly larger deviation from square planarity of $[PdL^4]^{2+}$ than for the other palladium(II) complexes discussed



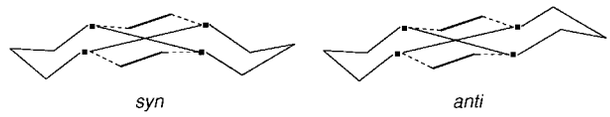


Fig. 2 The two ligand configurations found in complexes of Ni^{2+}, Pd^{2+} and Pt^{2+} of 14-membered tetrathiamacrocycles (experimentally observed geometries: *syn* for PdL^{2}, $PdL^{3'}$, PdL^{8}, PtL^{8}, NiL^{6}, NiL^{7} and *anti* for PdL^{1}, NiL^{5}, NiL^{8})

here (see *trans* angles in Table 4). The phenyl-substituted five-membered chelate ring has, similar to that in $[PdL^{2}]^{2+}$, an envelope conformation. The other two five-membered rings have λ and δ conformation, respectively. The six-membered chelate ring has a chair conformation, pointing to the same side of the chromophore as that of the phenyl substituent.

Preorganization

A preorganized compound is one that only requires minimum structural changes to become co-ordinated to a metal centre. Consequently, the extent of preorganization is related to the extent to which the conformations of the free and the co-ordinated compound differ, and thus to the energy involved in enforcing the ligand conformation of the metal complex. Obviously, this contributes to the free energy of the metal complex and therefore to its stability. Since the preference for a certain co-ordination geometry differs from metal ion to metal ion (*e.g.* the extent of the preference for square planar over tetrahedral geometry or the ideal metal–ligand distance), the extent of preorganization is metal-ion specific and therefore also related to the metal-ion selectivity.

The extent of preorganization is only one of several variables that determine the stability of a co-ordination compound. Electronic effects, solvation and electrostatic and environmental effects in general are others, that are not considered here. Clearly, the hydroxy substituents used by us enhance the solubility through changes in the solvation (methyl substituents, owing to enhanced hydrophobicity, also influence the solvation) and the benzo-substituted five-membered chelates lead through electronic effects to differences in the formation enthalpies of the complexes. However, a number of studies have demonstrated that preorganization is an aspect of major importance.[2b,c,4]

Tetrathioether macrocycles are known generally to prefer exodentate conformations. There is strong evidence that this is a main reason for the small macrocyclic effect and consequently for the relatively small stability of the corresponding metal complexes.[19] Experimental studies include thermodynamic[5] as well as kinetic investigations,[6] and interpretations of the data have been based on structural studies,[16a,20–24] molecular mechanics and molecular dynamics calculations, including minimization of putative intermediates,[6] computation of the macrocycle hole size,[25] frequency analysis of the torsional movement of the ligand backbone[25] and the investigation of intramolecular sulfur–sulfur distances.[25]

Our simple approach uses the analysis of the preorganization of tetrathiamacrocyclic compounds based on two parameters, the strain-energy ratio of the free and the co-ordinated macrocycles, E_L/E_C, as a parameter involving thermodynamic aspects of the ligand reorganization, and the sum of the absolute values of the differences of the intramolecular sulfur–sulfur distances between the free and co-ordinated macrocycles, $\sum_{n=1}^{6} |\Delta d_n|$, as a measure of the structural reorganization. An important question to be answered in this study was whether there was a correlation of the two sets of data, *i.e.* whether the two methods would lead to similar interpretations. The analysis is based on experimentally determined structural data for tetrathiamacrocyclic compounds and their nickel(II), palladium(II) and platinum(II) complexes, and on molecular mechanics studies of these systems. The compounds considered include, apart from the new structures described in this paper, the published structures L^{0} and L^{5}–L^{7}.[16a,20–23]

Within the whole set of macrocycles, ten different conformations have been observed experimentally. These define the limits of the conformational space used in our molecular mechanics analysis of the free macrocycles. The experimentally determined structures of the whole set of complexes of the nickel group metals with these compounds adopt only two different conformations (see Fig. 2).

Substitution by a benzo ring leads to a flattening of the corresponding five-membered chelate ring, and the topology of the remaining structure is preserved. The influence of the benzo substituents on the ligand conformation is shown in Fig. 3, where the topology of the macrocycles L^{1}–L^{4} is presented together with the geometry found in the corresponding palladium complexes. The four sulfur atoms are roughly lying in a plane in free L^{1} and L^{3}. The intramolecular sulfur–sulfur distances are, due to the exodentate conformations in these macrocycles, longer than in the corresponding complexes (see also Table 5 below), especially for L^{1}, which is the least preorganized in the series. The phenyl substituents in L^{2}–L^{4} confirm the expected influence but also indicate that the extent of preorganization is limited and variable, and not only dependent on the number of phenyl rings (see also paragraph on structures above).

The strain-energy-based reorganization parameter E_L/E_C. The ratio of the strain energies in the conformation adopted in the free macrocycle (experimentally determined and/or global minimum within the well defined conformational space) and that adopted in the metal complex is a measure of the strain induced by the metal ion on the ligand (note that all contributions to the total strain energy involving the metal centre are excluded). Thus, a fully preorganized compound would lead to $E_L/E_C = 1$, and generally $E_L/E_C < 1$. We note that the energy difference $E_C^{tot} - E_L^{tot}$, *i.e.* the energy needed to obtain the conformation enforced by the metal ion, including enthalpy and entropy terms, as well as solvation and ion-pairing effects, might be a preferable parameter for quantitative thermodynamic studies. Such an approach would, however, ignore the fact that strain energies are relative energy terms and based on a number of approximations.[3d] We therefore prefer to use a relative parameter that is based on and correlated to but not directly used for quantitative thermodynamic considerations. Apart from the most simple form of such a parameter (E_L/E_C), we have tested other possible terms, such as $(E_C - E_L)/(E_C + E_L)$, which lead to correlations of similar quality. It should be noted here that, independently of the approach used, the free macrocycles and the metal complexes are generally defined by a cluster of conformers. Thus, E_L and E_C should represent the weighted average of the corresponding strain energies. A similar comment applies to the structural reorganization parameter $\sum_{n=1}^{6} |\Delta d_n|$, see below. Based on the limited conformational analysis (see above) and the desired simplicity of the method, we have based our present analysis on the strain energies and structural properties of the lowest-energy conformers.

The data presented in Table 5 indicate that, with one exception (L^{2}), the conformation analysed experimentally corresponds to the minimum-energy structure. Based on the strain-

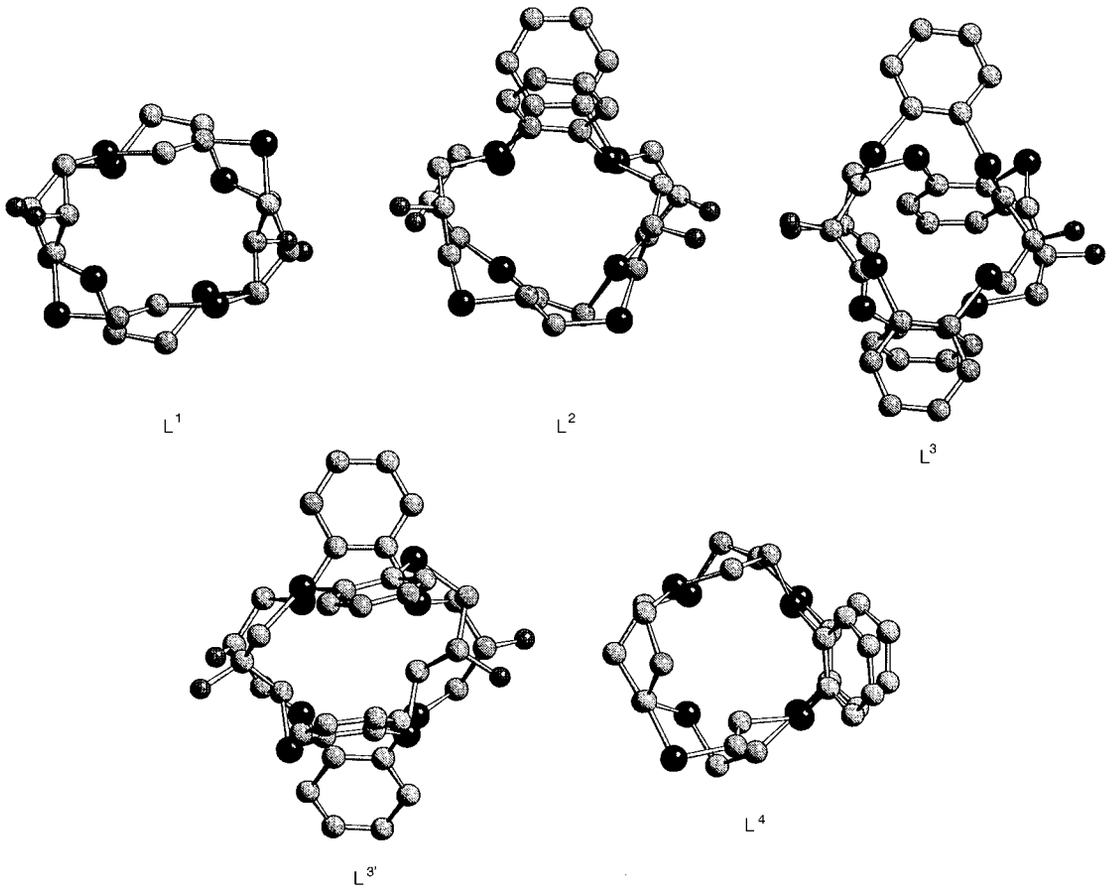


Fig. 3 Visualization of the structural differences between L^1, L^2, L^3, $L^{3'}$ and L^4 as free macrocycles (front) and in the conformation enforced by palladium(II) (background)

Table 5 Strain energies of the free macrocycles (E_L), of the ligands in the metal complexes (E_C), and thermodynamic and structural reorganization parameters E_L/E_C and $\sum_{n=1}^{6} |\Delta d_n|$, respectively

	L^1	L^2	L^3	$L^{3'}$	L^4	L^5	L^6	L^7		L^0	
$E_L^{x\text{-}ray}$/kJ mol^{-1}	13.05	22.41	11.27	—	7.73	19.66	20.27	38.17	↙	4.16	↘
E_L^{min}/kJ mol^{-1}	12.04	14.29	11.27	13.34	7.73	19.51	20.27	37.50		4.16	
	$[PdL^1]^{2+}$	$[PdL^2]^{2+}$	$[PdL^3]^{2+}$	$[PdL^{3'}]^{2+}$	$[PdL^4]^{2+}$	$[NiL^5]^{2+}$	$[NiL^6]^{2+}$	$[NiL^7]^{2+}$	$[NiL^0]^{2+}$	$[PdL^0]^{2+}$	$[PtL^0]^{2+}$
$E_C^{x\text{-}ray}$/kJ mol^{-1}	25.37	23.13	20.11	20.27	10.54	27.96	30.96	63.91	19.92	16.54	16.54
$\sum_{n=1}^{6} \|\Delta d_n\|$/Å	12.34	5.49	5.52	5.15	5.69	4.80	7.59	8.83	13.30	12.33	12.22
$E_L^{min}/E_C^{x\text{-}ray}$	0.47	0.62	0.56	0.66	0.73	0.70	0.65	0.59	0.21	0.25	0.25

energy-based reorganization parameter E_L/E_C the set of compounds considered may be separated arbitrarily into two groups, one with $E_L/E_C < 0.5$ and the other, more highly preorganized one, with $E_L/E_C > 0.5$. All substituted macrocyclic thioethers fall in the latter, more highly preorganized group. Further interpretations, based on these data alone, are clearly not warranted.

The structural reorganization parameter $\sum_{n=1}^{6} |\Delta d_n|$. The structural reorganization of the tetrathiamacrocycles, upon coordination to a metal centre, is described by the sum of the displacements of the donor atoms due to complexation. This is approximated by the sum of all absolute values of the differences between d_n (see Fig. 4, $n = 1$–6) in the free and coordinated macrocycles. This treatment is based on the assumption that the compounds do not fold and therefore do not lead to shorter intramolecular sulfur–sulfur distances than observed in the complexes. Owing to the preference of tetrathiamacrocycles for exodentate conformations, folding has not been observed so far. A structural parameter based on distances from the putative metal centre would require one to choose arbitrarily such a point in the free macrocycle. With the unsymmetrical geometries of the systems discussed here, involving endo- and exo-dentate conformations, this is not a relevant alternative. Small $\sum_{n=1}^{6} |\Delta d_n|$ values are indicative of highly preorganized compounds. These data are also given in Table 5. There is a reasonably good overall correlation between the structural and the strain-energy-based reorganization parameters.

Interpretations, implications and conclusions

As already mentioned, the ligand preorganization and, therefore, the reorganization parameters, are metal-ion dependent. Thus, a more relevant picture emerges when the reorganization parameters are listed in dependence of the metal ion (see Table 6).

For the nickel(II) series we find a high extent of preorganization for the cyclohexyl- and cyclopentyl-substituted macro-

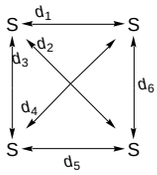


Fig. 4 The six intramolecular sulfur–sulfur distances of tetrathiamacrocycles

cycles. This is in reasonable agreement with the general trends emerging from experimentally determined thermodynamic data for a series of copper-(II) and -(I) compounds.[5d] Note however, that the comparison is not entirely relevant, since the preorganization is a metal-ion-dependent entity. This is especially true for the comparison with copper(I) which, in contrast to nickel(II), prefers tetrahedral co-ordination geometry. The known low extent of preorganization of the unsubstituted macrocycle L^0, *i.e.* the fully exodentate conformation, correlates well with a large structural and a very small strain-energy-based reorganization parameter.

The results obtained in the nickel(II) series for L^0 are comparable with those in the palladium(II) series. The same behaviour is also observed for $[PtL^0]^{2+}$ (see Table 5). This is, due to the known similarity in the steric demand and preferences of the two metal centres, not unexpected. An interesting question is why increasing substitution with phenyl rings does not necessarily lead to enhanced preorganization. For the palladium(II) series the calculated differences in preorganization between L^2, L^3 and $L^{3'}$ are not significant but, based on simple steric reasons, one might have expected an enhanced preorganization for L^3 and $L^{3'}$. Here, molecular mechanics calculations are an important tool in addition to the argumentation based on simple molecular models. Two possible reasons for the unexpected ordering are the half *endo*/half *exo* conformations observed for L^3 (see Fig. 3) and the flattening of the five-membered chelate rings discussed above. Note that electronic factors might further destabilize complexes of benzo-substituted macrocycles. These are not included in our present analysis.

Other structural and thermodynamic parameters such as parameters based on torsional angles might also be used to describe the preorganization of macrocycles. However, it seems that none would lead to more easily accessible, more general or more accurate results. One aspect that has not been considered and discussed so far is the orientation of the sulfur lone pairs, *i.e.* a possible destabilization by misdirected valences. There is no reason why this could not be included in our treatment as an additional perturbation. However, in order to keep the model as simple as possible, and realizing the good quality of the results and the inherent limitations, this does not seem to be a reasonable addition.

The two reorganization parameters E_L/E_C and $\sum_{n=1}^{6} |\Delta d_n|$ lead to easily accessible information on the preorganization of tetrathiamacrocycles, and thus to information on one of the main factors influencing the complex stability of these systems. This provides support to the design of new, highly selective complexing agents. Similar techniques should be applicable to other types of compounds, including different ring sizes, other donor sets and open chains. However, in other systems, the predominance of preorganization over electronic and environmental effects (*e.g.* solvation and ion pairing) might vanish to some extent, and one has to be careful in these cases to prevent oversimplifications.

Experimental

Spectroscopy and analyses

Proton and ^{13}C NMR spectra were recorded at 25 °C on a Bruker AS200 spectrometer. Elemental analyses are from the microanalytical laboratory of our department. The FAB and chemical ionization (CI) mass spectra were recorded with a Finnigan 8400 mass spectrometer; FAB spectra were obtained using a 3-nitrobenzyl alcohol matrix.

Table 6 Values of E_L/E_C and $\sum_{n=1}^{6} |\Delta d_n|$ for complexes of nickel(II) and palladium(II) with 14-membered tetrathiamacrocyclic ligands

	$[NiL^5]^{2+}$	$[NiL^6]^{2+}$	$[NiL^7]^{2+}$	$[NiL^0]^{2+}$	
E_L/E_C	0.70	0.65	0.59	0.21	
$\sum_{n=1}^{6} \|\Delta d_n\|$/Å	4.80	7.59	8.83	13.30	
	$[PdL^{3'}]^{2+}$	$[PdL^2]^{2+}$	$[PdL^3]^{2+}$	$[PdL^1]^{2+}$	$[PdL^0]^{2+}$
E_L/E_C	0.66	0.62	0.56	0.47	0.25
$\sum_{n=1}^{6} \|\Delta d_n\|$/Å	5.15	5.49	5.52	12.34*	12.33

* A conformer with a 1 kJ mol^{-1} higher strain energy has a value of $\sum_{n=1}^{6} |\Delta d_n| = 9.62$ Å.

Molecular mechanics

For the force-field calculations MOMEC[26] with a published force field was used.[27,28] Parameter values, not presented before, involve interactions between thioether sulfur (SW), hydroxo oxygen (OW), aromatic carbon (CA), aliphatic carbon (CT) and hydrogen (H). The following new parameters have been developed for this study, by fitting the parameter values to obtain minimum root-mean-square (r.m.s.) shifts between experimentally determined and computed data for all relevant structures available in the Cambridge Structural Data Base (23 structures): bonding interaction (k/mdyn $Å^{-1}$, r_o/Å), SW–CA 4.0, 1.765; valence angle interaction (k/mdyn Å rad^{-2}, θ_o/rad), CT–OW–H 0.35, 1.870; CA–SW–CT 0.50, 1.740; SW–CA–CA 0.45, 2.094; and torsion-angle interaction [(k/mdyn Å), *m*(integer), φ_o/rad], CA–CA 0.06, 2, 1.571.

Crystallography

For all structures, cell constants were determined by a least-squares fit to the setting parameters of the independent reflections. Data were measured on a Siemens Syntex, Nicolet R3 diffractometer with Mo-Kα radiation ($\lambda = 0.7107$ Å, limits in Table 7) and a graphite monochromator, operating in the ω-scan mode ($[PdL^{3'}]^{2+}$ was measured at 193 K, all other structures at room temperature). Data reduction, Lorentz-polarization and empirical absorption corrections were applied. The structures were solved by direct methods (L^1, L^3, L^4) and the Patterson method (L^2, $[PdL^1]Cl_2 \cdot 2H_2O$, $[PdL^2][PF_6]_2$, $[PdL^{3'}][PF_6]Cl$, $[PdL^4][PF_6]_2$) respectively, and refined by full-matrix least-squares analyses: L^1–L^4, $[PdL^2][PF_6]_2$, $[PdL^4][PF_6]_2$;[29a] $[PdL^1]Cl_2 \cdot 2H_2O$;[29b] $[PdL^{3'}][PF_6]Cl$.[29c] All non-hydrogen atoms were refined anisotropically. All hydrogen atoms, which were not located in the Fourier-difference map, were included at calculated sites, except for structure $[PdL^{3'}]^{2+}$ where they were refined. Scattering factors were taken from ref. 30. Crystallographic data are given in Table 7.

Atomic coordinates, thermal parameters, and bond lengths and angles have been deposited at the Cambridge Crystallographic Data Centre (CCDC). See Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1997, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 186/474.

Materials

The solvents were dried by standard methods. Ethane-1,2-dithiol was obtained from Aldrich and used without further

Table 7 Crystallographic data for the four tetrathiamacrocycles and the four palladium(II) complexes at room temperature

	L^1	L^2	L^3/L^{30}	L^4	$[PdL^1]Cl_2\cdot 2H_2O$	$[PdL^2][PF_6]_2$	$[PdL^{3'}][PF_6]Cl$	$[PdL^4][PF_6]_2$
Formula	$C_{10}H_{20}O_2S_4$	$C_{14}H_{20}O_2S_4$	$C_{18}H_{20}O_2S_4$/ $C_{18}H_{20}O_3S_4$	$C_{13}H_{18}S_4$	$C_{10}H_{20}Cl_2O_2PdS_4\cdot 2H_2O$	$C_{14}H_{20}F_{12}O_2P_2PdS_4$	$C_{18}H_{20}ClF_6OPPdS_4$	$C_{13}H_{18}F_{12}P_2PdS_4$
M	300.51	348.55	809.19 = 396.59 + 412.59	302.53	513.86	744.89	683.40	698.87
Crystal system	Monoclinic	Monoclinic	Triclinic	Monoclinic	Monoclinic	Monoclinic	Triclinic	Orthorhombic
Space group	$C2/c$	$P2_1/n$	$P\bar{1}$	$P2_1/c$	$P2_1/a$	$P2_1/n$	$P\bar{1}$	$Pnma$ [a]
a/Å	9.408(2)	11.915(4)	9.114(4)	13.631(8)	7.065(4)	8.482(3)	7.282(1)	13.863(6)
b/Å	17.967(5)	11.101(3)	14.241(3)	5.530(4)	17.919(9)	10.403(3)	11.023(3)	10.517(3)
c/Å	9.090(2)	12.483(4)	14.711(7)	18.33(1)	7.282(4)	26.98(1)	14.929(3)	15.624(5)
α/°			93.34(4)				78.11(2)	
β/°	116.08(2)	96.77(3)	94.26(4)	91.32(5)	91.71(2)	95.43(4)	80.78(2)	
γ/°			97.01(4)				83.54(2)	
U/Å^3	1380.1	1644.4	1885.5	1381.3	921.5	2370.0	1153.6	2278.0
Z	4	4	2	4	2	4	2	4
Crystal size/mm	0.15 × 0.40 × 0.60	0.40 × 0.50 × 0.95	0.10 × 0.30 × 0.75	0.10 × 0.25 × 0.95	0.05 × 0.40 × 0.60	0.20 × 0.45 × 0.55	0.20 × 0.30 × 0.55	0.15 × 0.20 × 0.90
2θ Range/°	3–57	3–50	3–46	3–57.5	3–57.5	3–54	3–50	3–60
D_c/g cm^{-3}	1.45	1.41	1.43	1.46	1.85	2.08	1.97	2.04
Reflections measured	3627	3088	5419	4083	2475	6664	4091	3769
Unique reflections	1768	1863	3328	1938	1993	4663	4091	1906
F(000)	640	736	848	640	520	1472	680	1376
R_{int}	0.05	*b*	0.092	0.034	*b*	0.045	*b*	*b*
μ/mm^{-1}	0.65	0.55	0.49	0.64	1.85	1.35	1.42	1.39
$R'(F)$ [c]	0.041	0.054	0.054	0.049	2.0	4.2	7.0 [d]	7.5
$R(F)$ [e]	0.045	0.064	0.064	0.058	2.2	4.8	2.7	8.4
No. parameters	74	182	444	155	98	317	309	161
Minimum, maximum peaks/e Å^{-3}	−0.31, 0.33	−0.34, 0.38	−0.33, 0.38	−0.38, 0.42	0.35, −0.35	−0.65, 0.96	0.5, −0.4	−1.03, 1.70 [a]

[a] The high residual electron density is caused by unusually high temperature factors of four fluorine atoms of one PF_6^- anion. The refinement of the data is not possible for the alternative space group $Pna2_1$. [b] Unique data set. [c] $\Sigma(|F_o| - |F_c|)w^{\frac{1}{2}}/\Sigma|F_o|w^{\frac{1}{2}}$. [d] $wR2 = [\Sigma w(F_o^2 - F_c^2)^2/\Sigma w(F_o^2)^2]^{\frac{1}{2}}$. [e] $\Sigma(||F_o| - |F_c||)/\Sigma|F_o|$.

purification. Benzene-1,2-dithiol was prepared according to published procedures.[31,32] A procedure analogous to that used for the synthesis of 1,10-dichloro-4,7-dithiadecane-2,9-diol[33] was used for the synthesis of *o*-phenylenedithio(3-chloropropan-2-ol). (η^5-Cyclopentadienyl)(η^6-1,2-dichlorobenzene)-iron(II) bis(hexafluorophosphate) was prepared by a published method.[34] 3,7-Dithianonane-1,9-dithiol was prepared by standard methods.[33]

Macrocycle syntheses

6,13-Dihydroxy-1,4,8,11-tetrathiacyclotetradecane (L^1). This was prepared as described elsewhere.[33] Crystals suitable for structure determination were obtained by recrystallization from acetone.

L^2. A three-necked, round-bottom flask (2 l) was fitted with an argon inlet and a condenser. The whole apparatus was maintained under argon for the duration of the reaction. The flask was charged with dry dmf (1.5 l) and Cs_2CO_3 (19.5 g, 60 mmol). To the hot (100 °C) and stirred dmf suspension was added dropwise over 18 h a solution (250 cm^3) of dmf containing 1,10-dichloro-4,7-dithiadecane-2,9-diol (11.0 g, 44 mmol)[33] and benzene-1,2-dithiol (5.6 g, 44 mmol). After cooling to room temperature the suspension was filtered and the solvent removed with a rotary evaporator. The oily residue was dissolved in dichloromethane (1 l), washed with water (1 l) and then twice with hydrochloric acid (20%, 1 l). The organic phase was dried with $MgSO_4$. Evaporation of the solvent produced 6.15 g (40%) of the crude product, which was recrystallized twice from ethanol to afford 4.5 g (13 mmol, 30%) of white crystals as a mixture of the *cis*- and *trans*-dihydroxy isomers (ratio 2.5 : 1). Crystals suitable for structure determination were obtained by crystallization from acetone. The two isomers were separated by fractional crystallization. The *anti* isomer is much more soluble in ethanol and acetone than the *syn*. Yield: 4.5 g (13 mmol, 30%) (*cis*). M.p.: 148 °C. ^{13}C NMR [50.0 MHz, $(CD_3)_2SO$]: δ 30.7, 32.7, 37.4, 69.8, 126.5, 128.5 and 135.4; (*trans*) 31.5, 36.5, 69.9, 126.7, 128.9 and 136.1: low resolution mass spectrometry (LRMS) (positive-ion FAB): *m/z* 348 (85, M^+) and 331 (58%, $M^+ - OH$) (Found: C, 48.45; H, 6.05; S, 36.55. Calc. for $C_{14}H_{20}O_2S_4$: C, 48.25; H, 5.75; S, 36.8%).

L^3. The synthesis of this compound followed essentially the same procedure as that for L^2. With equal amounts of base equivalents [CS_2CO_3 (45 mmol) in dry dmf], 5,6-benzo-1,10-dichloro-4,7-dithiadecane-2,9-diol[3] (10.8 g, 33 mmol) and benzene-1,2-dithiol (4.7 g, 33 mmol) were added during 24 h. Recrystallization of the oily product in ethanol (200 cm^3) afforded 2.5 g (6 mmol, 20%) of the pure *anti* isomer with only small traces of *syn* product. Slow evaporation of the mother-liquor afforded 40 mg of the pure crystalline *cis* product. Crystallization from acetone gave suitable crystals for a structure analysis. However, during the crystallization an oxygen uptake occurs and in the unit cell one of two molecules contains a sulfoxide group. Yield: 2.5 g (20%) (*trans*). M.p.: 210 °C. ^{13}C NMR [50.0 MHz, $(CD_3)_2SO$]: δ 38.1, 69.2, 127.1, 131.1 and 136.4; (*cis*) 36.4, 65.0, 126.6, 130.9 and 134.8. LRMS (positive-ion FAB): *m/z* 396 (100, M^+) and 379 (67%, $M^+ - OH$) (Found: C, 54.5; H, 5.1; S, 32.4. Calc. for $C_{18}H_{20}O_2S_4$: C, 54.5: H, 5.1; S, 32.3%).

L^4. A three-necked, round-bottom flask (4 l) fitted with septum, nitrogen inlet and condenser was dried and filled with nitrogen. The flask was charged with dried thf (2 l) and dried with potassium carbonate (2.5 g). This suspension was rigorously stirred. Dry (η^5-cyclopentadienyl)(η^6-1,2-dichlorobenzene)iron(II) bis(hexafluorophosphate) (2.5 g) (a) and dry 3,7-dithianonane-1,9-dithiol (1.4 g) (b) were dissolved in dry thf (200 cm^3) in separate round-bottom flasks (500 cm^3). The potassium carbonate suspension was heated to 60 °C and solutions (a) and (b) were added *via* a peristaltic pump within 24 h. The mixture was filtered and the filtrate reduced to a volume of 100 cm^3. This solution was washed with 0.05 mol dm^{-3} HCl (60 cm^3), and the organic phase dried with magnesium sulfate. The oily product was purified by column chromatography (silica gel deactivated with 10% water–acetone). The colourless, solid product was crystallized from dichloromethane. Yield: 0.55 g (30%). NMR (200 MHz, $CDCl_3$): ^{1}H, δ 1.61 (qnt, 2 H, J = 7.1), 2.59 (t, J = 7.0, 4 H), 2.69 (t, J = 6.8, 4 H), 3.23 (t, J = 6.8 Hz, 4 H), 7.16 (m, 2 H) and 7.31 (m, 2 H); ^{13}C, δ 28.42, 29.89, 30.18, 31.64, 127.03, 131.02 and 136.03. Electron-impact (EI) mass spectrum: *m/z* 140 (100) and 302 (80%, M^+) (Found: C, 51.2; H, 6.1; S, 41.7. Calc. for $C_{13}H_{18}S_4$: C, 51.6; H, 6.0; S, 42.4%).

Complex syntheses

$[PdL^1]Cl_2 \cdot 2H_2O$. Compound L^1 (80 mg, 0.26 mmol) and dipotassium tetrachloropalladate(II) (87 mg, 0.26 mmol) were added to methanol–water (1 : 1, 20 cm^3). After refluxing for 4 h an excess of ammonium hexafluorophosphate (400 mg, 24 mmol) was added to the hot and stirred solution. Yellow crystals (100 mg, 1.9 mmol; 65%), suitable for a structure determination, were obtained after filtration and standing for over 2 weeks. ^{13}C NMR [50.0 MHz, $(CD_3)_2SO$]: *trans*, δ 38.5, 42.4, 44.6, 45.3, 67.0 and 70.7 (Found: C, 23.1; H, 4.3; S, 24.3. Calc. for $C_{10}H_{20}Cl_2O_2PdS_4 \cdot 2H_2O$: C, 23.35; H, 4.7; S, 24.95%).

$[PdL^2][PF_6]_2$. Compound L^2 (108 mg, 0.3 mmol) and $K_2[PdCl_4]$ (101 mg, 0.3 mmol) were added to methanol–water (1 : 1, 20 cm^3). After refluxing for 4 h an excess of ammonium hexafluorophosphate (0.4 mg, 24 mmol) was added to the hot and stirred solution. Yellow-orange crystals (160 mg, 72%), suitable for a structure determination, were obtained after filtration and standing overnight. ^{13}C NMR [50.0 MHz, $(CD_3)_2SO$]: *cis*: δ 38.4, 41.6, 64.1, 131.8, 132.9 and 134.7 (Found: C, 22.3; H, 2.5; S, 16.6. Calc. for $C_{14}H_{20}F_{12}O_2P_2PdS_4$: C, 22.55; H, 2.7; S, 17.2%).

$[PdL^{3'}][PF_6]Cl$. Applying the same procedure as described above, and using L^3 (95 mg, 0.24 mmol) and $K_2[PdCl_4]$ (78 mg, 0.24 mmol) in methanol, 130 mg of an orange complex crystallized. Crystals suitable for structure determination were obtained by slow condensation of diethyl ether into a methanolic solution of the complex. Yield: 130 mg (1.9 mmol, 79%) (*anti*). ^{13}C NMR [50.0 MHz, $(CD_3)_2SO$]: *cis*, δ 47.7, 63.8, 132.2, 133.2 and 134.3; *trans*, δ 48.9, 49.1, 63.9, 67.1, 132.1, 132.4, 133.2, 133.6, 133.9 and 137.0 (Found: C, 31.3; H, 2.95; S, 18.35. Calc. for $C_{18}H_{20}ClF_6O_2PPdS_4$: C, 31.65; H, 2.95; S, 18.75%).

$[PdL^4][PF_6]_2$. Applying the same procedure as for $[PdL^2]^{2+}$, using L^4 (20 mg, 0.066 mmol) and $K_2[PdCl_4]$ (24 mg, 0.073 mmol) and crystallization from a small amount of water gave crystals suitable for a structure determination. Yield: 30 mg (65.2%). NMR [200 MHz, $(CD_3)_2SO$]: ^{13}C, δ 23.7, 33.8, 38.8, 47.1, 131.7, 132.2 and 136.0; ^{1}H, δ 1.90 (m, 1 H), 2.85 (d, 1 H, J = 17.0), 3.30 (m, 4 H), 3.70 (m, 4 H), 4.15 (m, 2 H), 4.50 (d, 2 H, J = 21.0 Hz), 7.75 (m, 2 H) and 7.95 (m, 2 H). Positive-ion (FAB): *m/z* 553 (60, $M^+ - PF_6$) and 406 (100%, $M - 2PF_6 - 2H$) (Found: C, 22.4; H, 3.0. Calc. for $C_{13}H_{18}F_{12}P_2PdS_4$: C, 22.35; H, 2.60%).

Acknowledgements

Financial support by the German Science Foundation (DFG), Degussa AG and by the Fond der Chemischen Industrie (FCI) is gratefully acknowledged. We congratulate Professor Walter Siebert on the occasion of his 60th birthday.

References

1 F. A. Cotton and G. Wilkinson, *Advanced Inorganic Chemistry*, 4th edn., VCH, Weinheim, 1985, p. 74; G. F. Smith and D. W. Margerum, *J. Chem. Soc., Chem. Commun.*, 1975, 807; L. S. W. S. Sokol, L. A. Ochrymowycz and D. B. Rorabacher, *Inorg. Chem.*, 1981, **20**, 3189; D. K. Cabbiness and D. Margerum, *J. Am. Chem. Soc.*, 1969, **91**, 6540.

2 (*a*) L. F. Lindoy, *The Chemistry of Macrocyclic Ligand Complexes*, Cambridge University Press, Cambridge, 1989; (*b*) B. Dietrich, P. Viout and J.-M. Lehn, *Macrocyclic Chemistry*, VCH, Weinheim, 1993; (*c*) A. E. Martell and R. D. Hancock, in *Crown Compounds*, ed. S. R. Cooper, VCH, Weinheim, 1992.

3 (*a*) M. G. B. Drew and D. Nicholson, *J. Chem. Soc., Dalton Trans.*, 1986, 1543; (*b*) R. D. Hancock, *Prog. Inorg. Chem.*, 1989, **37**, 187; (*c*) P. Comba, *Coord. Chem. Rev.*, 1993, **123**, 1; (*d*) P. Comba and T. W. Hambley, *Molecular Modeling of Inorganic Compounds*, VCH, Weinheim, 1995.

4 D. J. Cram, T. Kaneda, R. C. Helgeson and G. M. Liu, *J. Am. Chem. Soc.*, 1979, **99**, 948; D. J. Cram and G. M. Liu, *J. Am. Chem. Soc.*, 1985, **107**, 3657.

5 (*a*) D. H. Williams and D. H. Busch, *J. Am. Chem. Soc.*, 1965, **87**, 4644; (*b*) R. D. Hancock, *Acc. Chem. Res.*, 1990, **23**, 253; (*c*) L. F. Lindoy, *Prog. Macrocyclic Chem.*, 1986, **33**, 53; (*d*) L. A. Ochrymowycz and D. B. Rorabacher, *Inorg. Chem.*, 1995, **34**, 357.

6 L. Aronne, Q. Yu, L. A. Ochrymowycz and D. B. Rorabacher, *Inorg. Chem.*, 1995, **34**, 1844.

7 C. Nave and M. R. Truter, *J. Chem. Soc., Dalton Trans.*, 1974, 2351; E. B. Fleischer and S. W. Hawkinson, *Inorg. Chem.*, 1969, **8**, 2402; P. O. Whip, M. F. Bailey and N. F. Curtis, *J. Chem. Soc. A*, 1970, 1956; J. D. Dunitz and P. Seiler, *Acta Crystallogr., Sect. B*, 1974, **30**, 2739; M. Dobler, J. D. Dunitz and P. Seiler, *Acta Crystallogr., Sect. B*, 1974, **30**, 2741; M. Dobler and R. P. Phizackerley, *Acta Crystallogr., Sect. B*, 1974, **30**, 2746; M. Mercer and M. R. Truter, *J. Chem. Soc., Dalton Trans.*, 1973, 2215.

8 R. D. Hancock in *Perspectives in Coordination Chemistry*, eds. A. F. Williams, C. Floriani and A. E. Merbach, VHCA and VCH, Basel, Weinheim, 1992, p. 129.

9 J. M. Desper and S. H. Gellman, *J. Am. Chem. Soc.*, 1990, **112**, 6732; *J. Am. Chem. Soc.*, 1991, **113**, 704; J. M. Desper, S. H. Gellman, R. E. Wolf, jun. and S. R. Cooper, *J. Am. Chem. Soc.*, 1991, **113**, 8663; A. Y. Nazarenko, R. M. Izatt, J. D. Lamb, J. M. Desper, B. E. Matysak and S. H. Gellman, *Inorg. Chem.*, 1992, **31**, 3990; R. E. Wolf, jun., J. R. Hartman, M. E. Storey, B. M. Foxman and S. R. Cooper, *J. Am. Chem. Soc.*, 1987, **109**, 4328.

10 P. J. Blower and S. R. Cooper, *Inorg. Chem.*, 1987, **26**, 2009; R. E. J. Wolf, J. R. Hartman, L. A. Ochrymowycz and S. R. Cooper, *Inorg. Synth.*, 1989, **25**, 122; J. Buter and R. M. Kellogg, *Org. Synth.*, 1987, **65**, 150.

11 J. F. Bunnett and H. J. Hermann, *J. Org. Chem.*, 1971, **36**, 4081.

12 S. J. Rosca and S. Rosca, *Rev. Chim.* (Bucharest), 1974, **25**, 461; C. C. Lee, U. S. Gill, M. Iqbal, C. I. Azogu and R. G. Sutherland, *J. Organomet. Chem.*, 1982, **231**, 151; A. S. Abd-El-Aziz, C. C. Lee, A. Piorko, R. G. Sutherland, R. L. Choudhury and U. S. Gil, *J. Organomet. Chem.*, 1986, **315**, 79; A. S. Abd-El-Aziz, K. M. Epp, C. R. deDenus and G. Fisher-Smith, *Organometallics*, 1994, **13**, 2299.

13 A. S. Abd-El-Aziz, C. C. Lee, A. Piorko and R. G. Sutherland, *J. Organomet. Chem.*, 1988, **348**, 95.

14 R. C. Cambie, S. A. Coulson, L. G. Mackay, S. J. Janssen, P. S. Rutledge and P. D. Woodgate, *J. Organomet. Chem.*, 1991, **409**, 385.

15 E. Keller, SCHAKAL 92, *J. Appl. Crystallogr.*, 1989, **22**, 19.

16 (*a*) R. E. DeSimone and M. D. Glick, *J. Am. Chem. Soc.*, 1976, **98**, 762; (*b*) S. R. Cooper and R. E. Wolf, jun., *J. Am. Chem. Soc.*, 1987, **109**, 4328.

17 (*a*) J. M. Desper and S. H. Gellman, *J. Am. Chem. Soc.*, 1990, **112**, 6732; (*b*) J. M. Desper, S. H. Gellman and S. R. Cooper, *J. Am. Chem. Soc.*, 1991, **113**, 8663.

18 S. R. Cooper and S. C. Rawle, *Struct. Bonding* (*Berlin*), 1990, **72**, 1; A. J. Blake and M. Schröder, *Adv. Inorg. Chem.*, 1990, **35**, 1; S. G. Murray and F. R. Hartley, *Chem. Rev.*, 1981, **81**, 365.

19 J. D. Lamb, R. M. Izatt, J. J. Christensen and D. J. Eatough, *Coordination Chemistry of Macrocyclic Compounds*, Plenum, New York, 1979, ch. 3; R. M. Izatt, J. S. Bradshaw and S. A. Nielson, *Chem. Rev.*, 1985, **85**, 271.

20 J. M. Desper, J. R. Vyvyan, M. J. Mayer, L. A. Ochrymowycz and S. H. Gellman, *Inorg. Chem.*, 1993, **32**, 381.

21 P. H. Davis, L. K. White and R. L. Belford, *Inorg. Chem.*, 1975, **14**, 1753.

22 M. N. Bell, A. J. Blake, R. O. Gould, A. J. Holder, T. I. Hyde, A. J. Lavery, G. Reid and M. Schröder, *J. Inclusion Phenom.*, 1987, **5**, 169.

23 D. Waknine, M. J. Heeg, J. F. Endicott and L. A. Ochrymowycz, *Inorg. Chem.*, 1991, **30**, 3691.

24 G. H. Robinson, Hongwing Zhang and J. L. Atwood, *Organometallics*, 1987, **6**, 887; N. Galesic, M. Herceg and D. Sevdic, *Acta Crystallogr., Sect. C*, 1986, **42**, 565.

25 G. A. Forsyth and J. C. Lockhart, *J. Chem. Soc., Dalton Trans.*, 1994, 2243.

26 P. Comba, T. W. Hambley and N. Okon, *MOMEC, a Molecular Mechanics Package for Inorganic Compounds*, Altenhoff & Schmitz, Dortmund, 1995.

27 P. V. Bernhardt and P. Comba, *Inorg. Chem.*, 1992, **31**, 2638.

28 P. Comba, H. Jakob, B. Nuber and B. K. Keppler, *Inorg. Chem.*, 1994, **33**, 3396; P. Comba and M. Ströhle, *Helv. Chim. Acta*, 1995, **78**, 2042.

29 (*a*) SHELXTL PLUS, Release 4.11/V, Siemens Analytical X-Ray Instruments, Madison, WI, 1990; (*b*) XLS, Release 4.2/800, Siemens Analytical X-Ray Instruments, Madison, WI, 1990; (*c*) G. M. Sheldrick, SHELXL 93, University of Göttingen, 1993.

30 *International Tables for X-Ray Crystallography*, Kynoch Press, Birmingham, 1974, vol. 4.

31 R. Adams and A. Ferretti, *Org. Synth.*, 1962, **42**, 54.

32 S. Hünig and E. Fleckenstein, *Liebigs Ann. Chem.*, 1970, **738**, 192.

33 L. A. Ochrymowycz and D. B. Rorabacher, *Inorg. Chem.*, 1988, **27**, 2164.

34 A. N. Nesmeyanow, N. A. Vol′kenau and I. N. Bolesova, *Tetrahedron Lett.*, 1963, **25**, 1725.

Received 19*th November* 1996; *Paper* 6/07859A