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The importance of interactions between methyl groups and aromatic rings in homo and hetero-cyclophane structures. A molecular mechanics and x-ray crystallographic investigation

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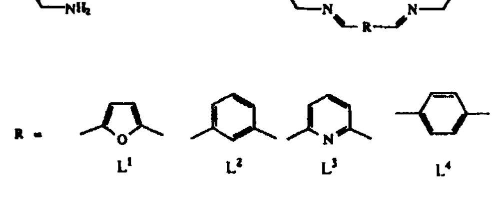
A series of macrocycles (L^1, L^2, L^3, L^4) generated by the [2+3] Schiff base condensation of tris-2-aminoethylamine with a series of aromatic aldehydes have been investigated. The crystal structure of [L^3], $CHCl_3$, $2H_2O$ is reported here to complete the set of structural data for these macrocycles. In all four structures, the three aromatic rings adopt a triangular disposition around the long ellipsoidal diameter, the $N_{br}-N_{br}$ axis. In these structures, attractive H...π interactions predominate and the conformations are rationalised by molecular mechanics calculations which show the importance of these interactions.

INTRODUCTION

Recent theories of π-interaction[1] stress the need to be aware of π-charge considerations when estimating crystal packing or other geometric relationships which involve interactions between aromatic rings. The well-defined geometric requirements for stabilising interactions between aromatic molecules can be rationalised using a simple charge distribution model[2], which considers separately the σ-framework and π-system. Thus, electrostatic effects favour face-to-edge contacts between the negative π-charge and positive σ-bonding framework involving the H-C σ-bond. When π-systems are aligned parallel, rather than edge-to-face, the same σ-dipolar/π-charge electrostatic arrangements favour an offset 'staggered' stacking of aromatic rings over the eclipsed/columnar stacking arrangement.

The theory has been applied to rationalise both inter- and intra-molecular interactions in aromatic molecules ranging from tertiary structure of proteins[3] to conformational preferences of aromatic molecules.[4] Heteroaromatic molecules can also be included in the theory, upon modification of π and σ charges deriving from the polarisation generated by the heteroatom. However, in this case favourable edge-on interaction require a positively charged atom in the vertical T-group and a negatively charged atom in the horizontal group. Edge-on lone pair/π-system interactions are classified as repulsive and therefore destabilizing.

The series of macrobicycles generated by [2+3] Schiff-base condensation of tris-2-aminoethylamine (tren) with dialdehydes (eqn 1) should provide an opportunity to illustrate the effect of π-interactions on conformation, unless steric constraints restrict configurational freedom



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so severely that π-π interactions are negligible in comparison with other steric repulsions. In hexa-Schiff base cryptands so far isolated in the metal free state and structurally characterised, the three aromatic rings adopt a triangular disposition around the long ellipsoidal diameter, the $N_{br}-N_{br}$ axis. This means that each α-CH or heteroatom is directed towards the face of an adjacent π system in a symmetric, mutually face-to-edge arrangement encompassing all three rings. Such a geometry suggests that face-to-edge π-σ interactions may contribute to the stability of this conformation. It is intriguing however that the solid state configuration of the 2, 5-linked furan-derived macrobicycle L^1 [5] is similar to that of the homoaromatic L^2 (p-benzene linkage),[6] despite the fact that the former has an oxygen atom, with negatively charged lone pairs and the latter an aromatic hydrogen atom with partial positive charge, both directed towards the negatively charged face of the π-system. However the differences may be explained by the increase in ring size from five to six and the concomitant change in geometry of the linkage.

Isolation of the pyridinophane, L^3, in crystalline form provided a useful opportunity to further examine the contribution of π interactions to the choice of conformation in this series. Apart from substitution of the heteroatom N, for C-H, this cryptand is identical with the cyclophane L^2 whose structure has previously been determined[6]. In that structure each C-H moiety has six close interactions with the phenyl ring carbons of an adjacent ring. These H...C distances; 2.78–3.02, 2.93–3.08, 2.80–3.05Å in the three cases, are in the range associated with edge to face interactions.* As expected these short distances gives rise to a shift in the NMR resonance, well to high field of the normal 7–8 ppm aromatic range.

It is thus of considerable interest to examine the extent to which this close approach of aromatic rings is altered in the analogous heteroaromatic L^3 structure. In this work, we describe the crystal structure of L^3, $2H_2O$, $CHCl_3$. While this work was in progress, the crystal structure of L^3 was reported.[9] The cell parameters were totally different and no solvent molecules were located in the unitcell.

We also report molecular mechanics calculations on L^1, L^2 and L^3 as well as on L^4 with a para-phenyl linkage. The structure of this latter compound L^4 has previously been reported[10]. These calculations were undertaken in order to ascertain whether any significant differences exist between predicted and observed structures and if so to consider whether the difference may be rationalised in terms of π-charge considerations.

There are two main aims to this work. First is to examine the crystal structures and to investigate the importance of electrostatic interactions involving the aromatic rings. Second is to establish whether such effects can be simulated by the traditional molecular mechanics forcefield, as examplified by the Dreiding II forcefield used in this work, where non-bonded interactions between atoms are simulated by van der Waals interactions (quantified by a Lennard-Jones or Buckingham potential) and an electrostatic potential using equation 1.

$$E_{electrostatic} = \sum q_i q_j / (\epsilon r_{ij})$$

where q_i, q_j are the partial atomic charges on atoms i and j, ϵ is the dielectric constant and r_{ij} is the distance between atoms i and j. Significant problems arise with the use of this equation. First, it is artificial as the molecular wavefunction only provides the electron density distribution in the molecule and ways of partitioning this onto individual atoms are somewhat inexact; second, it provides an inaccurate indication of the charge distribution of the molecule as the effect of lone pairs, and π clouds are ignored. A further complication arises because in the most favoured method of calculating atomic charges (the electrostatic potential method[11, 12]) atomic charges have proved to be dependent upon the conformation of the molecule.[13] Several approaches have been put forward to provide a more realistic simulation. These have included using multipole analysis[14], as well as using a distribution of point charges around each atom. In this latter method[1], for aromatic atoms, additional point charges are included above and below the atoms to represent the π cloud. None of these methods have yet been included in a generally available molecular mechanics program. Our approach in this work is to establish whether such a method would be necessary to explain the structures of the cryptates described in this work.

EXPERIMENTAL

X-ray Crystallography: Crystal Data for (1), L^3, $CHCl_3$, $2H_2O$, $C_{34}H_{44}N_{11}Cl_3O_2$, M = 673.8, a = 11.389(12), b = 10.686(11), c = 31.958(12) Å, β = 93.2(1), U = 3883.2Å3, F(000) = 1432, $d_m = 1{\cdot}16\ gcm^{-3}$, $d_c = 1.15\ gcm^{-3}$, Z = 4, MoKα (λ = 0.7107Å), $\mu = 1.47\ cm^{-1}$, spacegroup $P2_1/c$. A crystal of approximate size 0.3 * 0.3

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*There is considerable debate as to what distance constitutes a H...C interaction and what distance just represents van der Waals interactions. Viswamitra et al[7] have suggested H...C distances of 2.69Å or less to alkynes, 2.77Å or less to alkenes. Rzepa et al[8] have carried out a search of the Cambridge Crystallographic Database and found five structures in which an O-H proton was < 2.5Å from both carbon atoms of a C=C bond and have suggested that H...C distances should be significantly less than the combined H and C van der Waals radii which they estimated at 2.8Å. They also reference several O-H...π interactions where shortest contacts between the hydrogen atom and the plane of the ring is between 2.2 and 2.5Å. Our view is that a H...π interaction is not just indicated by the H...C distance but also by the spatial relationship between the C-H vector and the position of the π electrons.

* 0.3 mm was mounted on a STOE-2 two-circle diffractometer to rotate around the a axis. Data were measured via ω scan with a 2θ maximum of 50°. Background counts were for 20 s and a scan rate of 0.033°/s was applied to a width of $(1.5 + \sin\mu/\tan\theta)$. No decay in intensity was observed for the standard reflections. 4701 independent reflections were measured of which 2203 with $I > 2\sigma(I)$ were used in subsequent calculations. The structure was solved by direct methods. Hydrogen atoms on the ligand and solvent chloroform were placed in calculated positions. Hydrogen atoms on the water molecules were not located. All non-hydrogen atoms were refined aniostropically and hydrogen atoms isotropically. The structure was refined by full-matrix least squares with a weighting scheme of $w = 1/[\sigma^2(F) + 0.003F^2]$. In the final cycle of refinement, no shift was greater than 0.1 σ. In the final difference Fourier map, maximum and minimum peaks were at 0.75 and -0.53 eÅ^{-3} respectively. Calculations were performed using Shelx76[15] and some of our own programs on the Amdahl 5870 at the University of Reading. The final R value was 0.079 (Rw = 0.077). Positional parameters are given in Table 1, torsion angles in Table 2 and hydrogen bond details in Table 3. Molecular dimensions, thermal parameters, hydrogen atom positions and structure factor tables have been deposited as Supplementary Material.

MOLECULAR MECHANICS

Molecular mechanics calculations were carried out using the CERIUS software[16] on a Silicon Graphics Indigo R4000 workstation. The default Dreiding II force field was employed. The crystal structures of L^1, L^2, L^3 and L^4 were used as starting models although C-H distances were idealised at 1.08Å. Calculations were carried out first with zero charges on the atoms, and then with charges calculated by the electrostatic potential method via MOPAC[17]. In the calculations with charges, a unit dielectric was employed. The structures were minimised using the steepest descents method followed by the Newton-Raphson method.

TABLE 1 Atomic coordinates (*10**4) for (1) with estimated standard deviations in parentheses

ATOM	*X*	*Y*	*Z*
N(1)	−1231(7)	5261(6)	8934(2)
C(1A)	−1164(12)	4530(10)	9325(3)
C(2A)	−1604(11)	5270(10)	9672(3)
N(3A)	−2855(9)	5405(8)	9645(3)
C(4A)	−3261(12)	6465(9)	9578(3)
C(5A)	−4519(7)	6709(10)	9518(3)
C(6A)	−5282(11)	5765(9)	9492(3)
C(7A)	−6434(11)	6001(11)	9431(3)
C(8A)	−6807(11)	7278(8)	9476(3)
C(9A)	−5905(7)	8189(7)	9504(2)
N(10A)	−4863(7)	7948(6)	9533(2)
C(11A)	−6183(9)	9568(8)	9539(3)
N(12A)	−7252(8)	9866(7)	9541(2)
C(13A)	−7478(10)	11226(9)	9630(3)
C(14A)	−8468(9)	11671(9)	9314(3)
C(1B)	−198(10)	6066(9)	8884(3)
C(2B)	−424(9)	7210(8)	8615(3)
N(3B)	−962(7)	8211(6)	8878(2)
C(4B)	−1909(10)	8685(9)	8768(3)
C(5B)	−2383(10)	9834(8)	8974(3)
C(6B)	−1866(9)	10270(8)	9300(2)
C(7B)	−2448(9)	11335(9)	9479(3)
C(8B)	−3540(10)	11760(10)	9284(4)
C(9B)	−3897(10)	11284(9)	8905(3)
N(10B)	−3393(9)	10228(7)	8748(2)
C(11B)	−4931(8)	11708(7)	8686(3)
N(12B)	−5444(9)	12686(9)	8803(3)
C(13B)	−6443(13)	13074(10)	8567(4)
C(14B)	−7460(11)	13139(11)	8831(3)
C(1C)	−1418(9)	4373(9)	8545(3)
C(2C)	−2714(9)	4336(8)	8439(3)
N(3C)	−3178(7)	5435(7)	8207(3)
C(4C)	−4071(11)	6037(10)	8352(3)
C(5C)	−4550(8)	7180(7)	8122(3)
N(10C)	−5462(7)	7581(6)	8334(2)
C(9C)	−6031(7)	8570(7)	8199(2)
C(8C)	−5698(9)	9152(9)	7807(3)
C(7C)	−4739(12)	8752(11)	7645(4)
C(6C)	−4111(11)	7669(8)	7794(3)
C(11C)	−7057(11)	8986(10)	8391(4)
N(12C)	−7826(7)	9804(7)	8240(2)
C(13C)	−8805(10)	10111(9)	8468(4)
C(14C)	−8876(9)	11564(7)	8563(3)
N(2)	−8010(7)	11831(6)	8887(2)
C(100)	−8825(14)	15665(11)	7560(3)
CL(1)	−8847(4)	14054(5)	7531(1)
CL(2)	−7921(4)	16023(3)	8009(1)
CL(3)	−8210(5)	16133(4)	7098(2)
O(100)	−8512(8)	11008(6)	7457(2)
O(200)	−0442(8)	11554(8)	10311(3)

RESULTS AND DISCUSSION

The crystal structure of L^3 is shown in Figure 1(a), together with the hydrogen bond scheme. Both water molecules are hydrogen bonded to two imine N-H groups and a chlorine atom of the chloroform molecule. A view of the structure down the N(bridgehead)...N-(bridgehead) vector is shown in Figure 1(b) and shows an eclipsed arrangement of the CH_2 groups adjacent to the bridgehead nitrogen atoms. Indeed as indicated by the torsion angles in Table 2, the macrocycle has approximate 3/m symmetry although there are significant disparities presumably due to packing effects and the formation of hydrogen bonds. All hydrogen bonds are listed in Table 3. In Figure 1(c), we show clearly the interaction between adjacent pyridine rings. The closest contact from the nitrogen atom of the pyridine ring to a carbon atom on an adjacent ring is 4.09Å. However there are also close contacts between the imide C-H groups adjacent to the pyridine ring and the adjacent pyridine ring with H...C distances of 3.07, 3.10, 3.02, 3.11 Å. Close contacts are also apparent to the adjacent C=N bonds (to C 3.16, 3.19, to N 3.36, 3.39). Other contacts in the other linkages are comparable. It may well be that it is these contacts which will be attractive in nature

Table 2 Torsion angles (°) in the crystal structure of (1)

C(1B)	N(1)	C(1A)	C(2A)	85.7
C(1C)	N(1)	C(1A)	C(2A)	−150.3
C(1A)	N(1)	C(1B)	C(2B)	−153.6
C(1C)	N(1)	C(1B)	C(2B)	82.1
C(1A)	N(1)	C(1C)	C(2C)	95.3
C(1B)	N(1)	C(1C)	C(2C)	−138.7
C(13A)	C(14A)	N(2)	C(14B)	−85.8
C(13A)	C(14A)	N(2)	C(14C)	147.9
C(13B)	C(14B)	N(2)	C(14A)	144.8
C(13B)	C(14B)	N(2)	C(14C)	−88.5
C(13C)	C(14C)	N(2)	C(14A)	−88.4
C(13C)	C(14C)	N(2)	C(14B)	145.2

				A	*B*	*C*
N(1)	C(1)	C(2)	N(3)	73.5	81.1	78.6
C(1)	C(2)	N(3)	C(4)	−113.1	−124.0	−127.3
C(2)	N(3)	C(4)	C(5)	176.1	−168.9	179.1
N(3)	C(4)	C(5)	N(10)	167.0	172.7	178.8
N(10)	C(9)	C(11)	N(12)	−175.1	−178.7	−165.9
C(9)	C(11)	N(12)	C(13)	172.7	178.3	179.5
C(11)	N(12)	C(13)	C(14)	135.6	121.9	122.8
N(12)	C(13)	C(14)	N(2)	−74.4	−81.2	−75.2

Table 3 Hydrogen bonds in (1)*

N(12C)...O(100)	2.88
N(3C)...O(100)	3.01 (−1-x, −0.5+y, 1.5−z)
O(100)...C1(1)	3.28
N(10C)...C1(2)	3.37 (−1+x, y, z)
N(12A)...O(200)	3.09
N(3B)...O(200)	2.98

*Symmetry element x,y,z unless otherwise stated.

(H...π) will govern the close proximity of the rings, rather than repulsions between the nitrogen atom and the adjacent rings which in any case are much further away.

STRUCTURAL COMPARISON

The structures of L^1, L^2 and L^4 are shown in Figures 2 and 4 in two projections, (a) first down the N(bridgehead)...N(bridgehead) vector and (b) second in a view perpendicular to that vector.

We compared the structures of L^1, L^2, L^3 and L^4 and relevant details are given in Tables 4 and 5. It is noticeable that most of the structures have significant distortions from threefold symmetry. This could be due to packing effects, particularly hydrogen bonding as L^1 contains one solvent water, and L^3 (this work) contains two solvent water molecules and one trichloromethane. On the other hand L^4 contains a crystallographically imposed C_3 axis. L^2 contains no solvent.

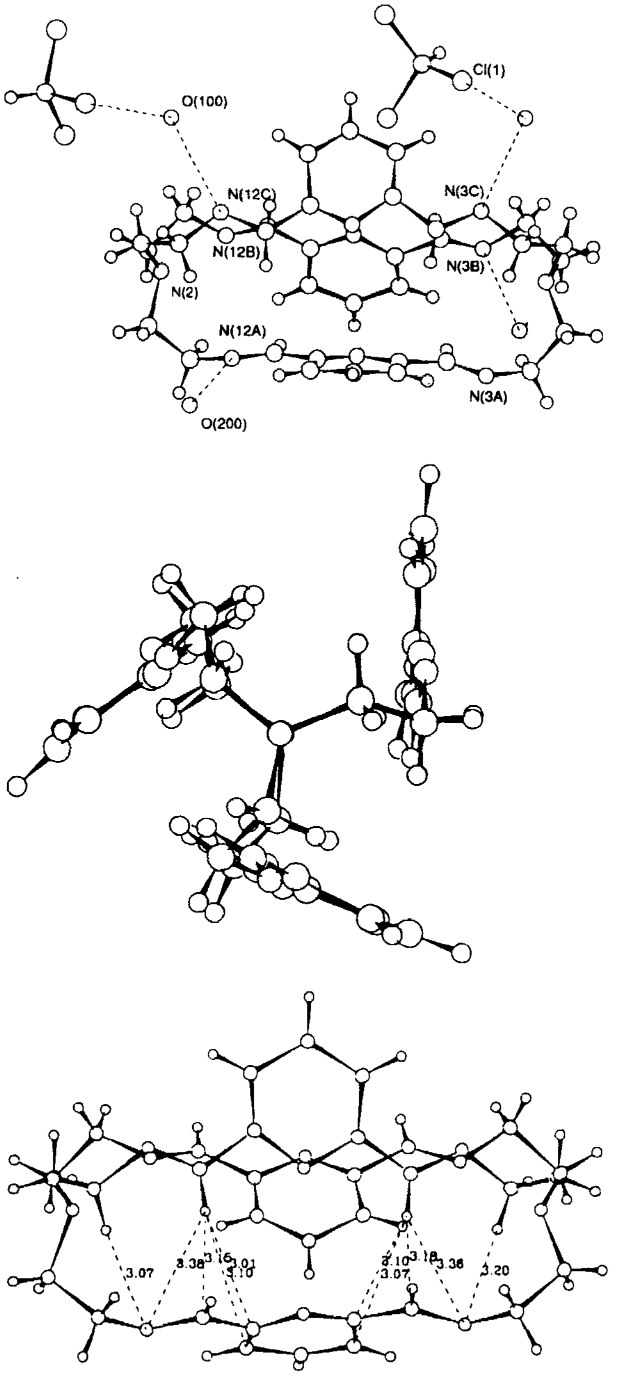

Figure 1 (a) View of L^3, showing the hydrogen bonding between the macrocycle and the water and trichloromethane molecules. (b) View of L^3, projected down the N(bridgehead)...N(bridgehead) vector. (c) View of L^3, showing the close contacts between the two C-H groups of one linkage with the imine group and aromatic pyridine ring of another. These contacts are values measured for the interaction between one linkage and another. Values in the other two interactions are similar but not equivalent.

The most striking aspect of the distortion from threefold symmetry is indicated by the angles between the phenyl rings which are perforce 60° in L^4. Values in L^1 and L^3 which contain hydrogen bonds, are very different

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*The previous structure determination of this ligand does not contain solvent. However the coordinates are not yet available.

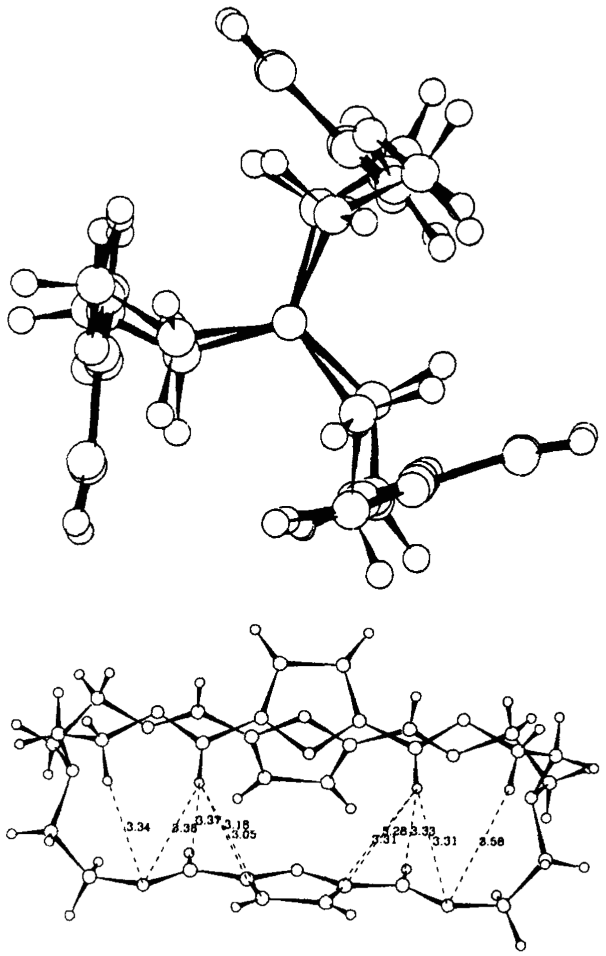

Figure 2 (a) View of L^1, projected down the N(bridgehead)... N(bridgehead) vector. (b) View of L^1, showing the close contacts between the two C-H groups of one linkage with the imine group and aromatic furan ring of another. These contacts are values measured for the interaction between one linkage and another. Values in the other two interactions are similar but not equivalent.

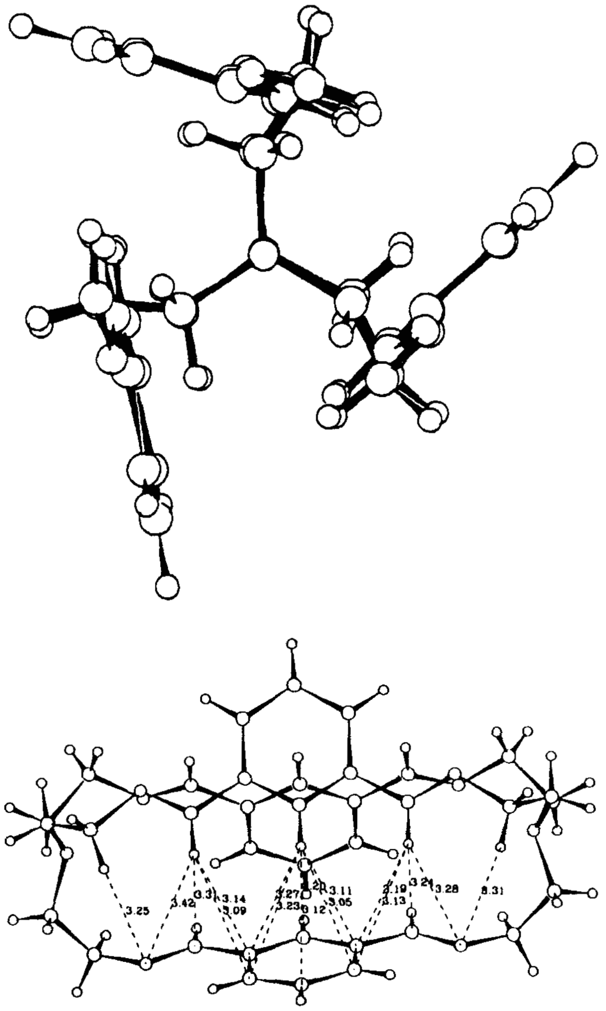

Figure 3 (a) View of L^2, projected down the N(bridgehead)...N (bridgehead) vector. (b) View of L^2, showing the close contacts between the two C-H groups of one linkage with the imine group and aromatic pyridine ring of another. These contacts are values measured for the interaction between one linkage and another. Values in the other two interactions are similar but not equivalent.

(51.2, 61.2, 67.6; 61.2, 66.7, 52.1°). However distortions are also found in L^2 where there is no solvent (56.0, 59.8, 64.2°) and this must be ascribed to packing effects, particularly as in all our molecular mechanics calculations, no significant deviation from threefold symmetry was observed. L^1, L^2 and L^3 show a predominantly eclipsed arrangement around the N...N vector as is apparent from Figures 1b, 2a and 3a while L^4 shows a staggered arrangement (Figure 4a).

As stated in the introduction, we were intrigued by the similarity in the structures of L^1, L^2 and L^3, given the different nature of the central atom in the bridge O, CH and N respectively).

We have already noted one reason for this with reference to L^3, and that is illustrated in Figure 1c, namely that the -CH groups adjacent to the ring form an attractive link to the aromatic rings and the adjacent double bonds in other linkages which may well override any repulsion between the negatively charged O (in the furan bridged L^1) or N (in the pyridine bridged L^3) and the aromatic rings, particularly as these unprotonated donor atoms are a long way from the rings.

This seems a logical reason for the similarity in the structures. However we wished to examine whether the traditional molecular mechanics forcefield with electrostatic terms described by equation (1) would be able to successfully model the molecular structures of L^1, L^2, L^3 and L^4. We first used the default DreidingII forcefield in CERIUS to optimise the geometry. In order to check on

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The structure of L^4 (Figure 4) is rather different as the linking group is paraphenyl. A consequence of this is that for each phenyl ring, two hydrogen atoms on one side are directed towards one of the other rings, and the two hydrogen atoms on the other side are directed towards the alternate ring. In both cases H...C distances are 3.22, 3.27Å with distances from the H to the phenyl ring plane of 2.28, 2.39Å. This structure is included for comparison and as a test of the molecular mechanics method.

Table 4 Selected Distances (Å) of atoms in aromatic rings to the least squares planes defined by adjacent aromatic rings

			molecular mechanics calculations	
		x-ray structure	*without charges*	*with charges*
L^1 R = furan	O (furan)	3.434	3.010	3.262
		3.263	3.010	3.249
		3.232	3.014	3.269
L^2 R = m-phenyl	C-H	3.642, 2.833	3.669, 2.792	3.641, 2.763
		3.551, 2.681	3.687, 2.796	3.658, 2.766
		3.548, 2.704	3.676, 2.802	3.647, 2.771
L^3 R = pyridine	N	3.747	3.655	3.753
		3.738	3.658	3.745
		3.905	3.659	3.764 ,
L^4 R = p-phenyl	C-H	3.051, 2.395	3.063, 2.374	3.064, 2.386
		2.936, 2.280	2.849, 2.061	2.834, 1.999
		2.936, 2.280	2.874, 2.044	2.859, 2.024
		3.051, 2.395	3.076, 2.038	3.091, 2.415
		3.051, 2.395	3.076, 2.382	3.091, 2.415
		2.936, 2.280	2.874, 2.044	2.859, 2.024
		3.051, 2.395	3.063, 2.374	3.064, 2.386
		2.936, 2.280	2.849, 2.016	2.834, 1.999
		2.936, 2.280	2.849, 2.016	2.834, 1.999
		3.051, 2.395	3.063, 2.374	3.064, 2.386
		3.051, 2.395	3.076, 2.382	3.091, 2.415
		2.936, 2.280	2.874, 2.043	2.859, 2.024

Table 5 The angles (°) between the ring normals to aromatic rings

		molecular mechanics	*calculations*
	x-ray structure	*without charges*	*with charges*
L^1 R = furan	51.2, 61.2, 67.6	60.1, 60.2, 59.8	59.2, 61.2, 59.7
L^2 R = m-phenyl	56.0, 59.8, 64.2	61.0, 59.6, 59.4	59.5, 59.4, 61.1
L^3 R = pyridine	61.2, 66.7, 52.1	59.8, 60.6, 59.6	61.1, 59.8, 59.5
L^4 R = p-phenyl	60.0, 60.0, 60.0	60.0, 60.0, 60.0	60.0, 60.0, 60.0

the validity of the calculated structures, these were then compared to the experimental structures by the calculation of an r.m.s. deviation. Because of the uncertainty of the positions of hydrogen atoms from the crystallographic investigations, their coordinates were ignored in the calculations. Fits were calculated using zero charges on the atoms, and then using charges calculated via the electrostatic potential method within MOPAC.[17] Agreements were usually improved when charges were included. In view of the distortions included by packing effects, these r.m.s. values of 0.2 to 0.3Å indicate a very good agreement.

We next looked at the crystal structure to see whether there was any significant difference between the positions of the oxygen atoms of the furan ring (in L^1), the nitrogen atom of the pyridine ring (in L^3) and the C-H (of the phenyl ring L^2) relative to the adjacent aromatic rings. In Table 4, we list the distances of these atoms from the planes of the adjacent aromatic rings. The mean distances of the furan oxygen atom is 3.31Å, of the pyridine nitrogen atom is 3.80Å and of the C-H group is 3.58, 2.74Å respectively. The difference between distances involving the furan oxygen and the pyridine nitrogen of 0.49Å is striking and must be due to the different steric requirements of the five and six-membered rings. This is borne out by a similar difference being obtained in the molecular mechanics calculations.

It is interesting that the deviation of the carbon atom of the C-H moiety at 3.58Å is significantly less than the value for the nitrogen atom at 3.80Å. This would confirm that the attraction between the C-H group and the aromatic ring is a factor in the overall structure of the m-phenyl ligand. Each hydrogen atom is similar in distance to the six carbon atoms of the aromatic ring with distances between 2.9 and 3.2Å.

These observations are borne out by our molecular mechanics calculations. In Table 4, we list results from calculations with and without charges. There are significantly better fits when charges are introduced. Thus with the furan structure, the distance is 3.01 without charges but 3.26 with charges (experimental is 3.31Å). Thus the negative charge on the oxygen atoms repels the aromatic ring. Note that the atomic charges on aromatic rings are slightly negative for carbon and slightly positive for hydrogen atoms. The inclusion of charges has made less effect on the pyridine structure (increase from 3.66 to 3.75Å compared to experimental 3.80Å), presumably because the atoms are much further away from each

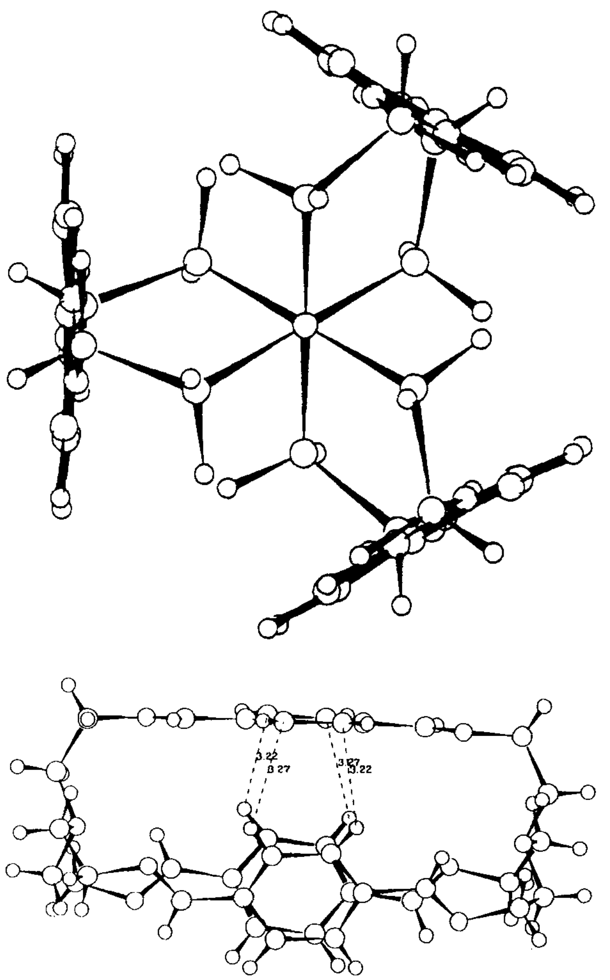

Figure 4 (a) View of L^2, projected down the N(bridgehead)... N(bridgehead) vector. (b) View of L^2, showing the close contacts between the two C-H groups of one linkage with the aromatic benzene ring of another.

other. However again inclusion of charges has led to a significantly better fit.

By contrast with the m-phenyl, the inclusion of charges has led to a decrease in distance (C 3.68 to 3.65Å, H 2.80 to 2.77Å) because of the attraction of the positively charged hydrogen atom to the negatively charged carbon atoms.

In all three cases, the inclusion of charges has led to a substantially better fit, indicating that steric effects are not the sole cause of variations between the structures. From these results, we would suggest that the traditional electrostatic summation over partial charges can give reasonable insights into atomic structure. It could be argued that this good fit is a consequence of the rather weak H...π interactions. With some of the much shorter H...C distances, found particularly for O-H...C interactions and quoted in ref 7, it may well much more difficult to reproduce the structure with regular molecular mechanics methods. However the molecular mechanics calculations have also shown that the H...π electrostatic interactions are important in these molecules.

Table 6 R.m.s values (Å) of molecular mechanics structure to the experimental structure (hydrogen atoms not included)

Compound	molecular mechanics calculations without charges	molecular mechanics calculations with charges
L^1 furan	0.40	0.33
L^2 m-phenyl	0.24	0.22
L^3 pyridine	0.34	0.30
L^4 p-phenyl	0.25	0.25

It is clear that the reason for the similarity in structure for furan, pyridine and p-benzene links is that both the steric constraints of the macrocycle and the attraction of the -CH to the imine double bond more than outweigh the repulsions between heteroatoms O and N from the adjacent aromatic ring.

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