Relief of steric strain by intramolecular C–H···O interactions: structural evidence for the 1,4-disubstituted cyclohexanes

Thomas Steiner * and Wolfram Saenger

Institut für Kristallographie, Freie Universität Berlin, Takustraße 6, D-14195 Berlin, Germany

Two crystal structures are reported where *trans*-cyclohexane-1,4-diol is observed in the unexpected biaxial conformation, even with its associated steric conflict between the substituents and the axial H-atoms of the cyclohexane moiety. In a consecutive database analysis of *trans*- and *cis*-1,4-disubstituted cyclohexanes, it is found that the steric distortions caused by axial substituents, X, depend strongly on the chemical nature of X. These distortions are surprisingly small for X = O and N, larger for X = S, and more pronounced for X = C. Cyclohexanes with axial O-substituents are almost unstrained. This is explained by intramolecular C–H···O interactions between the electron lone pair of the O-atom and the axial H-atoms, which allow shorter approach of O to H than of C to H. Reasons are given why the classification of these interactions as 'hydrogen bonds' is inadequate.

Introduction

It is well known that monosubstituted cyclohexanes prefer the chair conformation with the substituent in the equatorial position. This is because in the axial position, the substituent is involved in steric conflicts with two axial H(C) atoms, leading to distortion from ideal chair geometry. For *trans*-1,4-disubstituted cyclohexanes, the preference for the biequatorial conformation is necessarily more pronounced because the biaxial chair conformation is associated with steric conflicts with all four axial H(C) atoms. For *cis*-1,4-disubstituted cyclohexanes, chair inversion leads to a different situation only if the two substituents are different; in this case, the conformation with the bulkier substituent in the equatorial position is preferred so as to minimise steric conflicts. Only if both substituents are very bulky, a situation arises where *cis*-1,4-disubstituted cyclohexanes prefer the boat conformation. In solution, substituted cyclohexanes undergo rapid chair interconversion with the less favourable conformations having shorter lifetimes and hence smaller population densities.

In this contribution, we report crystal structures with cyclohexane conformations which are unexpected following the above principles. In a consecutive database analysis, it is found that for substituents with X = O in the axial position, the steric distortions are only small, and the preference to adopt equatorial positions in crystal structures are not very pronounced. This finding is discussed in the context of intramolecular C–H···O interactions which at least partially relieve the strain caused by the steric conflicts.

Results

Crystal structures

β-Cyclodextrin–*trans*-cyclohexane-1,4-diol·$5.4H_2O$. This study was prompted by experiments on the inclusion of cyclohexane-1,4-diol in the bio-organic macrocylic host molecule β-cyclodextrin (β-CD, cyclomaltoheptaose). Commercial cyclohexane-1,4-diol contains a mixture of the *cis* and *trans* isomers. As part of our work on cyclodextrin inclusion complexes,[1] we attempted separation of *cis*/*trans*-cyclohexane-1,4-diol by complexation with β-cyclodextrin. The basic idea was that due to the different shapes, the binding constants of the two isomers might be sufficiently different to allow separation by crystallisation as inclusion complex. For crystallisation, hot concentrated solutions of β-CD in water with a large excess (1 : 10 and more) of *cis*/*trans*-cyclohexane-1,4-diol were allowed to cool slowly to room temperature. X-Ray analysis of the formed crystals showed that they constitute the 1 : 1 complex of β-CD with the pure *trans*-isomer (**1**). Since *trans*-cyclohexane-1,4-diol is somewhat too small to fill the β-CD cavity completely, the remaining space hosts two molecules of crystal water. The inclusion geometry is shown in Fig. 1(*a*), the crystal packing in Fig. 1(*b*).

The observation that the *trans*-isomer of cyclohexane-1,4-diol can thus be isolated from a *cis*/*trans*-mixture is of interest, but more surprising is the conformation of the encapsulated molecule: the cyclohexane ring is in chair conformation with the biaxial orientation of the hydroxy groups, and not in the expected biequatorial form [Fig. 1(*a*)]. One of the hydroxy groups is placed near the cavity opening and engaged in hydrogen bonds with two neighbouring β-CD molecules, and the other hydroxy group is placed in the central part of the cavity and is in hydrogen bonding contact with one of the two water molecules included in the β-CD cavity [Fig. 1(*b*)].

We were puzzled that the inclusion of the biaxial conformer is preferred to that of the expected biequatorial form. Initially, we speculated that this could be due to more favourable hydrogen bonding interactions, or to a neater geometrical fit into the relatively rigidly confined cavity. All such possible explanations, however, left us unsatisfied, initiating a closer investigation of the solid state structures of 1,4-disubstituted cyclohexanes.

***trans*-Cyclohexane-1,4-diol.** Since the crystal structures neither of the *trans*, nor of the *cis* isomer of cyclohexane-1,4-diol had been published as yet, we attempted to grow crystals suitable for X-ray studies from the available *cis*/*trans*-mixture. Slow evaporation of EtOH solutions yields a large bulk of precipitate and some small crystals built of the pure *trans*-isomer, **2**. All attempts to grow crystals of the *cis*-isomer from the *cis*/*trans*-mixture, or cocrystals of both isomers, failed.

The crystal structure of **2** is peculiar as it contains *both* chair conformers of the *trans*-isomer, which coexist in the solid state [Fig. 2(*a*)]. In the biaxial conformer, the intramolecular contacts from the hydroxy O-atoms to the axial H-atoms of C2 and C3 have H···O distances of 2.71 and 2.67 Å, respectively, and angles at H of 96.1 and 94.2°, respectively (for normalized H-atom positions with C–H = 1.08 Å); the C···O distances are 2.990(2) and 2.955(2) Å, respectively. To see, if these contacts lead to a distortion of the chair geometry, both conformers are drawn in side-view in Fig. 2(*b*). Indeed, in the biaxial conformer, the C–O bond is slightly bent away from the molecular axis, forming an angle of 94.2° with the C1–C2′–C3 plane. This clearly reflects repulsion of O from the axial H-atoms and steric

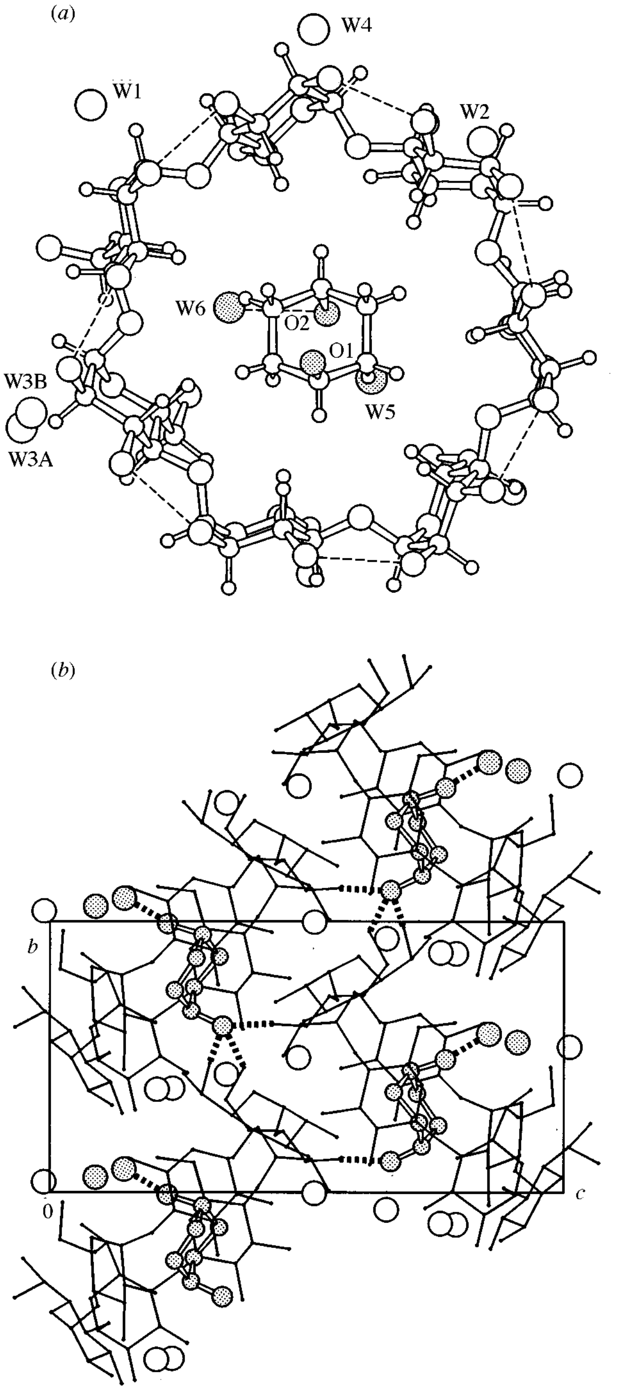


Fig. 1 Crystal structure of β-cyclodextrin–*trans*-cyclohexane-1,4-diol·$5.4H_2O$, **1**. (*a*) Shown in a projection along the β-CD molecular axis. O-atoms of the guest molecules are drawn shaded. Intramolecular O2···O3 hydrogen bonds are indicated by dashed lines. (*b*) Crystal packing shown in a projection along the crystallographic *a*-axis. β-CD molecules are drawn with thin lines, water molecules as large spheres. Guest molecules are drawn shaded. O···O distances suggestive of hydrogen bonding are drawn as dashed lines only when involving the *trans*-cyclohexane-1,4-diol molecules.

strain within the cyclohexane ring but, on the other hand, the distortion is obviously only small. In the biequatorial conformer such distortions also occur, but are only marginal.

In the crystal lattice, the biaxial conformer is placed on a crystallographic inversion centre, whereas the biequatorial conformer is in a general position. Therefore, the asymmetric crystal unit contains 1.5 molecules of **2**, and the crystal as a whole contains twice as many molecules in the biequatorial as in the biaxial conformation. In the crystal, molecules form layers parallel to the *a*,*b*-plane (Fig. 3). If layers with biaxial conformers

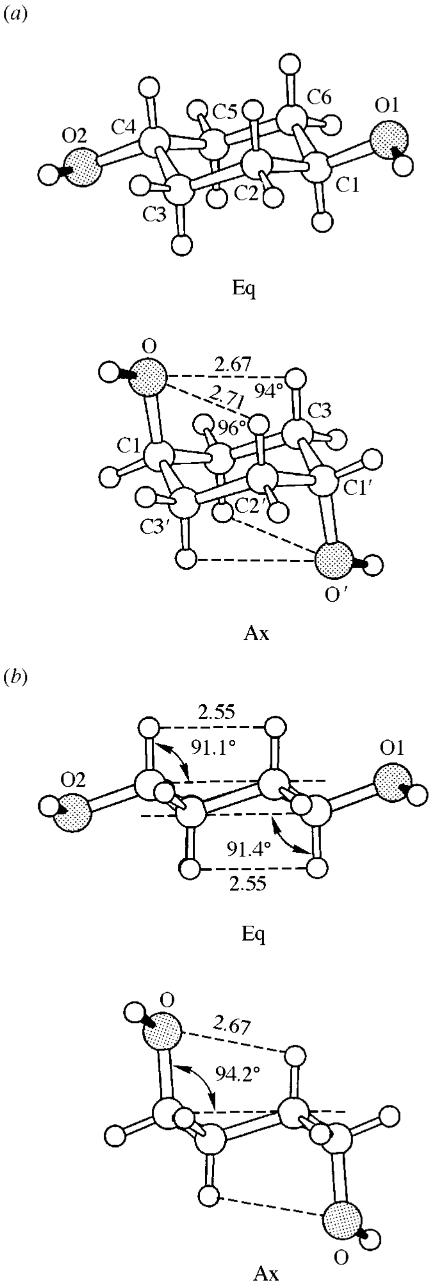


Fig. 2 Crystal structure of *trans*-cyclohexane-1,4-diol, **2**. (*a*) Molecular structure and atomic numbering scheme for both conformers. O-atoms are drawn shaded. For the biaxial conformer, intramolecular H···O distances are given in Å for normalised H-atom positions (C–H = 1.08 Å). (*b*) Both conformers shown in side-views. The angles between the axial substituents at C1 and C4 and the cyclohexane C1–C3–C5 plane are given.

are denoted Ax and those with biequatorial conformers Eq, the layer sequence is EqAxEq–EqAxEq–EqAxEq, in which molecules within each triple-layer are connected by infinite chains of O–H···O–H···O hydrogen bonds ('homodromic chains'), whereas between the triple-layers, there are only van der Waals contacts and C–H···O hydrogen bonds[2] (not shown).

A stringent explanation for the unexpected occurrence of both conformers in the crystal is not at hand. It can only be speculated that the very strong motif of cooperative homodromic hydrogen bonds can for steric reasons only be formed if both conformers are present, thereby inducing the formation of a complex crystal packing mode. In any case, the fact that the two conformers readily cocrystallize makes it unlikely that they are very different in energies. Note that the crystal of **2** can almost be considered as a binary crystal, *i.e.* as being composed of two kinds of molecules.

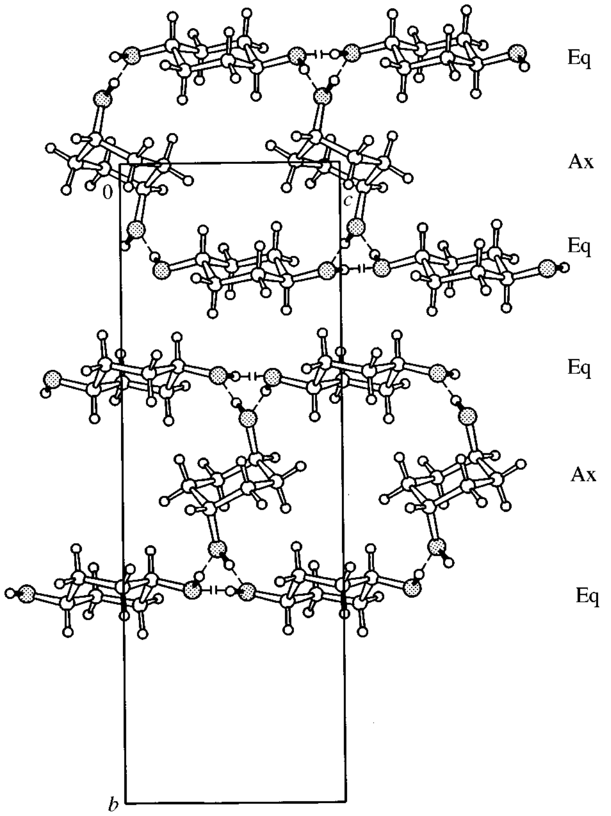
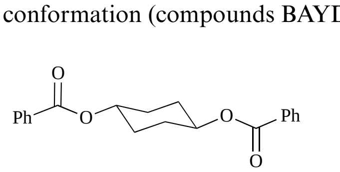


Fig. 3 Crystal packing of *trans*-cyclohexane-1,4-diol. Infinite hydrogen bond chains O1A–H···OB–H···O2A′–H···OB′–H *etc.* are formed, which run parallel to the crystallographic *a*-axis. Since this is the projection axis, these chains are seen from the end and appear as cyclic motifs.

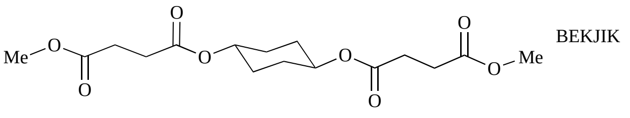
Database analysis

Having found two crystal structures with the biaxial conformer of *trans*-cyclohexane-1,4-diol, it was worth extending these studies to explore the occurrence and properties of axial substituents of cyclohexanes in the crystalline state in a database analysis (Cambridge Structural Database,[3] CSD, June 1997 update). This analysis was performed in three steps as follows.

***trans*-1,4-Disubstituted cyclohexanes.** To see whether the biaxial conformer of *trans*-1,4-disubstituted cyclohexane has also been found in other crystal structures, a search through CSD was performed (no substitutions at C2 and C3 allowed). Ninety-one *trans*-1,4-disubstituted cyclohexane moieties were found in 72 crystal structures. Of these, all are in chair conformations, 88 with biequatorial and three with biaxial orientation of the substituents. This clearly shows a strong general preference of the biequatorial form, as is to be anticipated. Only very few of the examples, however, can be directly compared with **2**, because of chemically very different substituents. Only two examples of *trans*-1,4-di-*O*-substituted cyclohexanes have been published, and both are found in the biequatorial conformation (compounds BAYDAG[4] and BEKJIK[5]).



BAYDAG



BEKJIK

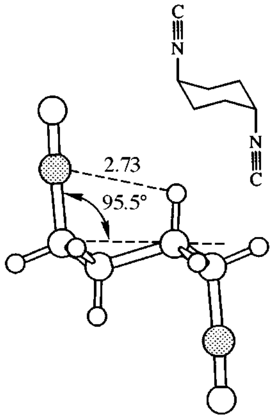
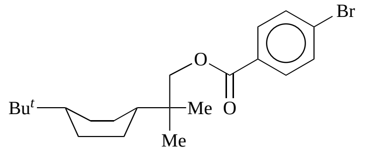


Fig. 4 Molecular structure of *trans*-1,4-diisocyanocyclohexane as observed in the crystal structure[6] (CSD reference code: YUNMOJ). N-atoms are shaded.

A closer look at the three biaxial conformers shows that they are chemically related. One is crystalline *trans*-1,4-diisocyanocyclohexane[6] (Fig. 4). The steric conflict between the isocyano substituents and the axial H-atoms causes only a slight bending (5.5°) of the C1–N vector away from the normal to the C1–C3–C5 plane, resembling the situation in the biaxial conformer of **2**. The other two examples are *trans*-1,4-diisocyanocyclohexanes, in which the isocyano groups carry organometallic and inorganic ligands, respectively. In these cases, the bending angles of C1–N away from the molecular axes are 8.2° [structure YUNMUP[6] with $Br_2(PEt_3)_2(CO)_2W$ ligands] and 5.1° (structure YUKJIX[7] with Mo_6O_{19} ligands).

These observations indicate that *trans*-1,4-disubstituted cyclohexanes with certain substituents like OH and −N≡C crystallize relatively easily in biaxial conformation, whereas others do not. This circumstance deserves closer investigation. No example is contained in the CSD where both conformers of a *trans*-1,4-disubstituted cyclohexane are found in the same crystal structure, making the structure of **2** a very exceptional case.

***cis*-1,4-Disubstituted cyclohexanes.** Crystal structures of *trans*-1,4-disubstituted cyclohexanes can give only very limited information on axial substituent positions, because these are in most cases avoided. Since in *cis*-1,4-disubstituted cyclohexanes with chair conformation, one of the substituents has to be in axial position, they should be better suited to characterize the distortions arising from different types of substituents X. In consequence, a CSD search on *cis*-1,4-disubstituted cyclohexanes was performed. Of the 28 moieties of this type found in 23 crystal structures, 27 are in chair, and one is in boat conformation. The latter is found in the crystal structure of compound CISJIX,[8] in which both substituents are very bulky.



CISJIX

The 27 *cis*-1,4-disubstituted cyclohexanes in chair conformations were divided into sets with common axial substituent [X = O, N, C(sp^2), *etc.*]. For these sets, the inclination angles *a* of the C1–X bond of the axial substituent with respect to the C1–C3–C5 plane are listed in Table 1. The differences between the sets are pronounced. Since in many of the crystal structures, H-atoms are not in realistic geometry or not given at all, the H···X contact geometries are not analysed systematically here.

The set with X = O is relatively large ($n = 9$), and exhibits a mean inclination angle of $a = 94.2°$, *i.e.* the C1–O bond is bent 4.2° from perpendicularity with respect to the cyclohexane ring. Incidentally, this is the same value as observed for the biaxial conformer of **2** [Fig. 2(*b*)], making the OH groups of **2** a very typical example for O-substituents in an axial orientation. Two further examples[9,10] are shown in Figs. 5(*a*) and 5(*b*), in which

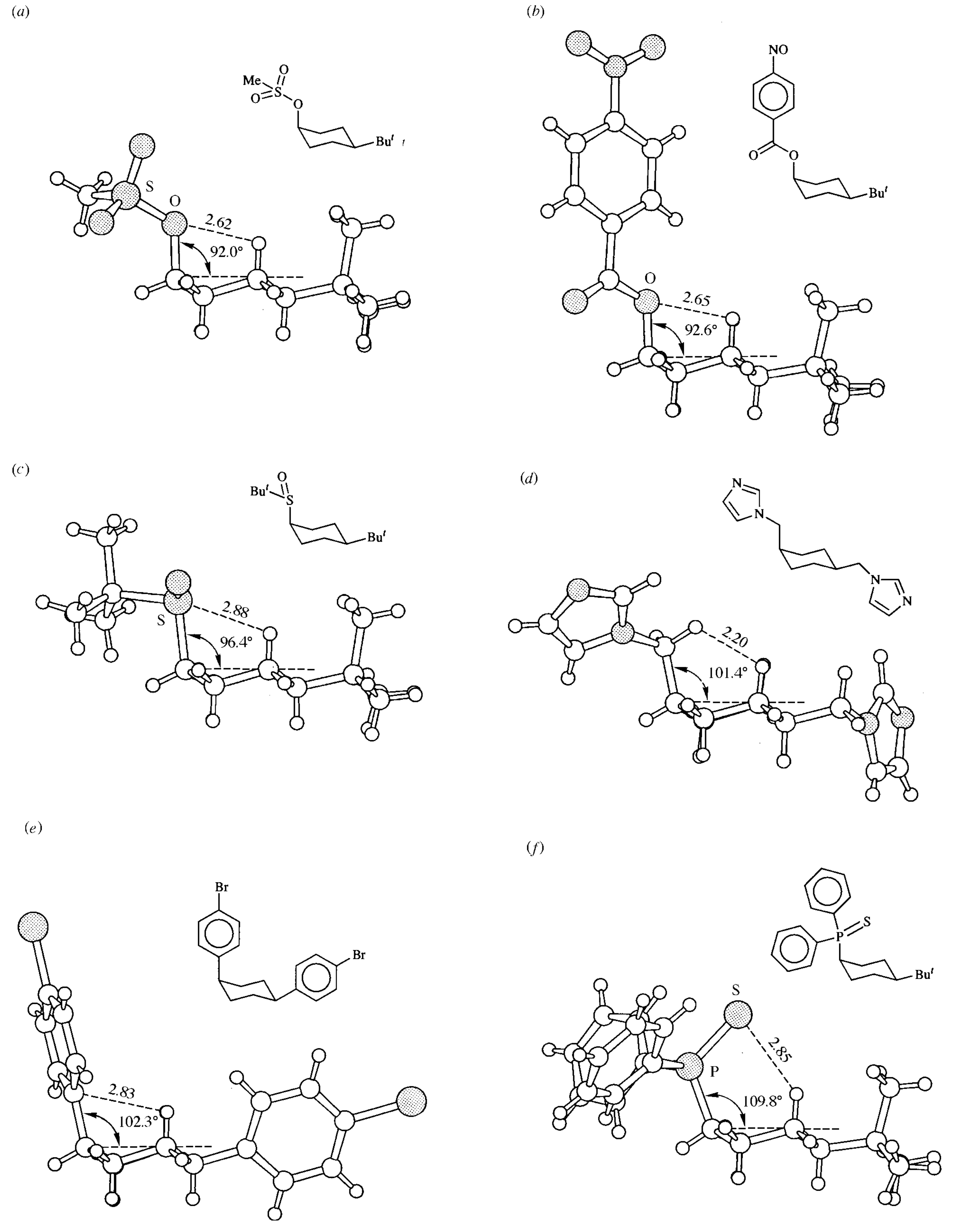


Fig. 5 Several representative *cis*-1,4-disubstituted cyclohexanes shown in projections parallel to the cyclohexane planes. Angles of the axial substituents with the C1–C3–C5 plane are indicated. For the H···X contacts between axial substituent and axial H-atoms, the distance for the shortest contact is given. (*a*) Example for an O–S substituent: compound KOTJOS (ref. 9). (*b*) Example for an O–C substituent: compound JULBEX (ref. 10). (*c*) Example for an S substituent with free electron pair: compound SEJFES (ref. 12). (*d*) Example for a C(sp^3)–H substituent: compound TAJVOP (ref. 14). (*e*) Example for a C(sp^2) substituent: compound LAPYEG (ref. 15). (*f*) Example for a P=S substituent: compound FUFCAK (ref. 18).

the bending of C1–O from perpendicularity are only 2.0 and 2.6°, respectively. These are almost unstrained cyclohexane conformations.

For axial N substituents, there is only a single example (compound CICSAI[11]), in which the nitrogen lone pair of a C1–N=C< group is oriented towards the axial cyclohexane H-atoms. The α-value of 94.1° indicates an only weakly strained conformation, similar as for X = O.

Table 1 Database results: *cis*-1,4-disubstituted cyclohexanes in chair conformation. X = axial substituent (at C1). *a* = angle between the C1–X bond and the cyclohexane C1–C3–C5 plane

Axial substituent X	*n*	α-range/°	mean α/°
O	9	92.0–95.9	94.2
N	1		94.1
S|	1		96.4
–C≡N	1		96.4
Br	1		99.7
$C(sp^3)$–H	4	100.0–101.8	101.0
$C(sp^2)$	7	99.6–105.1	102.5
SO_2	2	104.4–104.8	104.6
P=S	1		109.8

For S-substituents having a free electron pair that can be oriented towards the axial H-atoms, there is only one example,[12] shown in Fig. 5(*c*). The *a*-angle of 96.4° indicates increased steric strain compared to X = O or N. For X = Br, there is also only one example (compound BCOCHX[13]), in which the angle *a* is 99.7°.

The C-substituents must be subdivided according to the different hybridisation states of C. For C1–C(sp^3), only axial substituents are found which carry at least one H-atom on C. Then, C(sp^3) is oriented staggered with respect to C1, and the C–H bond is involved in a short contact with the axial cyclohexane H atoms with typical H · · · H separations around 2.2 Å. Due to this steric conflict, the C1–C bond is on average bent away by 11.0° from the cyclohexane axis, indicating appreciable strain. A typical example[14] is shown in Fig. 5(*d*). C1–C(sp^3) which carries only non-H substituents is so bulky that it has never been found axially oriented in the crystal structure of a 1,4-disubstituted cyclohexane. For axial C(sp^2) substituents, the C1–C bond is on the average bent by 12.1° from the C1–C3–C5 axis, *i.e.* the strain is significantly larger than for C(sp^3)–H; an example[15] is shown in Fig. 5(*e*). For axial C(sp^1) substituents, only one example has been published with a –C≡N ligand (VEVCEO[16]), which causes only relatively small distortion, *a* = 96.4° (notably, however, *trans*-cyclohexane-1,4-dicarbonitrile with two –C≡N ligands crystallises in biequatorial conformation[17]).

For bulkier substituents like SO_2Ph or PPh_2S, the strain can further increase without yet forcing the cyclohexane ring to adopt boat conformation; the extreme example in the CSD is for PPh_2S,[18] *a* = 109.8° [Fig. 5(*f*)].

If in *cis*-1,4-disubstituted cyclohexanes the substituents are different, a clearly bulkier substituent should prefer the equatorial position. For the structures analyzed here, this is in fact obeyed in all but one case. The single exception is the organometallic compound KAZTOU,[19] which carries four *cis*-1,4-methylcyclohexyloxy ligands; of these, only two are symmetry independent, one having the O-atom and one having the methyl group in axial position [Fig. 6(*a*)]. The different degrees of strain are also in this case reflected in the different bending angles of the C–X bond from the cyclohexane plane [Fig. 6(*b*)].

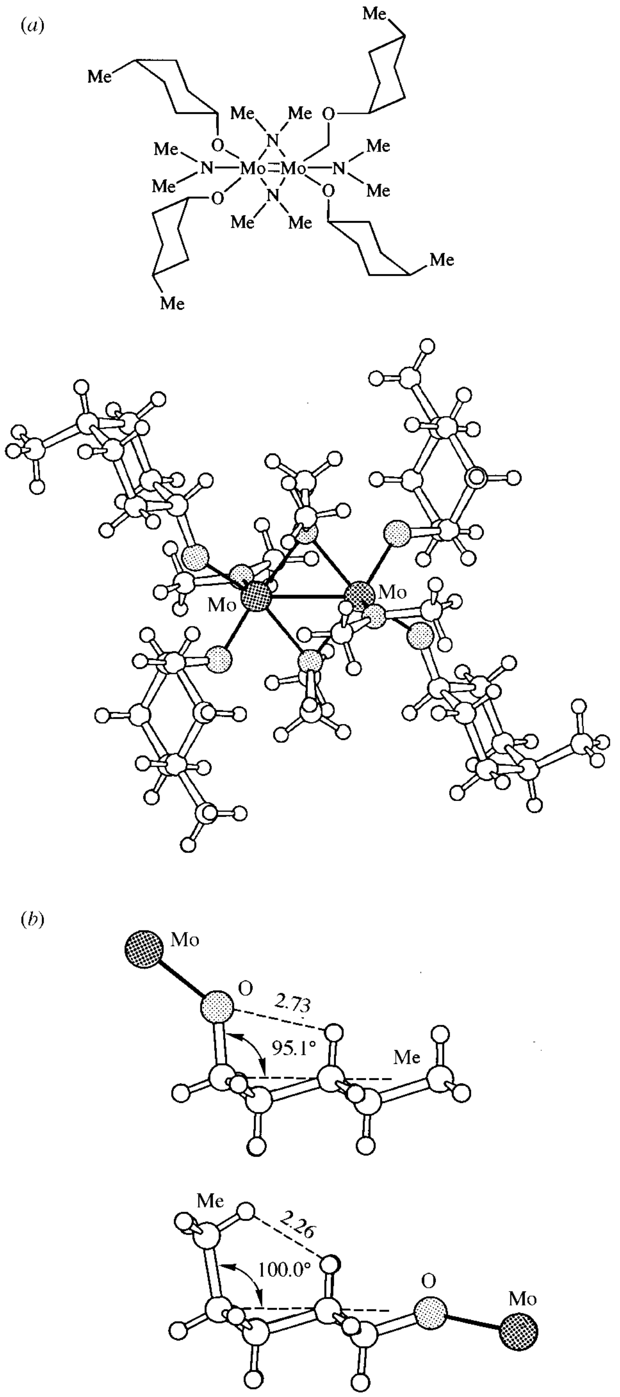


Fig. 6 Compound KAZTOU (ref. 19). (*a*) Formula and molecular structure. In the crystal lattice, the molecule is placed on an inversion centre, so that only two of the four cyclohexyl ligands are symmetry-independent. (*b*) The two independent cyclohexyl ligands shown in side view.

***O*-Monosubstituted cyclohexanes.** If *O*-substituents cause only minor strain in cyclohexanes when in the axial position, they should also be found occasionally in this position in monosubstituted cyclohexanes. Therefore, the conformation of *O*-monosubstituted cyclohexanes was investigated in a CSD search. Out of 44 groups, eight were found with O in the axial position. This is a fraction of 18%. It must be stated, however, that all occur in organometallic compounds, where oxo-cyclohexane groups are frequently used as ligands. A typical example[20] is shown in Fig. 7. The extreme example in the CSD is compound ZAQWIX[21] (of the 8 cyclohexane ligands, only four are symmetry-independent; in three of these, the O-atom is in an axial position). Although organic and organometallic compounds cannot be compared without reservations, this clearly shows that in monosubstituted cyclohexanes, the O-atom in axial position is by far not as unfavourable than might initially be expected.

The intramolecular C–H · · · O contacts. The data in Table 1 give a hierarchical order of substituents in terms of causing distortions when in the axial position of cyclohexane. The O- and N-atoms clearly cause the smallest distortions and therefore the smallest strain. In some cases, O-substituted cyclohexanes seem to be almost unstrained when O is in the axial position. This cannot be explained by purely steric reasons, because the van der Waals radii of O and C(sp^2) are almost identical[22] [compare Figs. 5(*b*) and 5(*e*)]. Therefore, it must be anticipated that the nature of the contacts between the substituent and the axial H-atoms is not the same for C and O. The

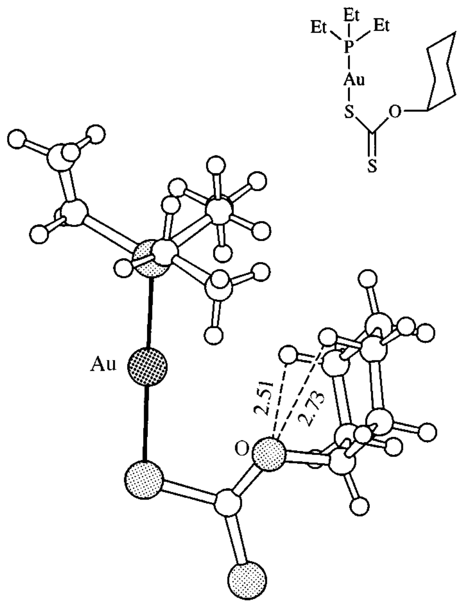
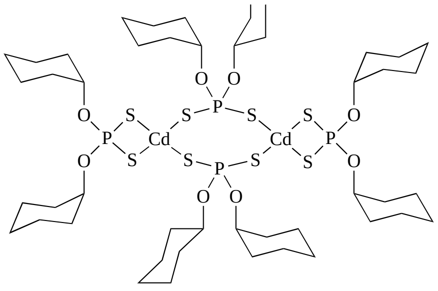


Fig. 7 Example for an *O*-monosubstituted cyclohexane with axially oriented substituent: compound YASJOR (ref. 20)

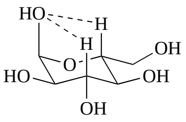


ZAQWIX

most obvious explanation of the discussed effects are favourable interactions between the O (or N, S) electron lone-pair and the axial cyclohexane H-atoms, which facilitate shorter approach of O to H than of C(sp^2) to H, so that the associated steric strain is reduced.

At this point, it must be asked whether there is a connection with C–H · · · O hydrogen bonding, a topic which is currently under intense investigation. In general, it is well established that C–H · · · O interactions may be of the hydrogen bond type, if the C–H · · · O angle is at least fairly linear, and the C–H · · · O contact itself is not a mere consequence of steric restrictions.[2] Then, hydrogen bond energies are around 1 kcal mol^{-1} for weakly polarized C–H groups (*ca.* 2 kcal mol^{-1} for more acidic C–H like in alkynes). For the present C–H · · · O contacts, however, neither of the above conditions is fulfilled: the C–H · · · O angles are far from linear, typically around 95° [Fig. 2(*a*)], and the C–H · · · O contacts occur within a frame of steric restrictions. When thinking on whether the discussed intramolecular C–H · · · O contacts might still represent weak 'hydrogen bonds', it must be stressed that even in liberal views, the minimal requirement for a hydrogen bond is that it provides a negative enthalpic contribution (that is: it must be 'bonding'). For the present case, this would mean that the biaxial conformer of *trans*-1,4-*O*-disubstituted cyclohexanes would have a lower energy than the biequatorial conformer which lacks such interactions, and should therefore be favoured. The structural data, however, leaves no doubt that also for O-substituents, the axial position is slightly less favourable than the equatorial one (though much less unfavourable than for C-substituents). This means that a classification of the discussed intramolecular C–H · · · O contacts as 'hydrogen bonds' is not justified.

As part of our work on C–H · · · O hydrogen bonds in carbohydrates, we have earlier reported related intramolecular contacts in pyranoses, such as in crystalline α-D-glucose.[23] These



contacts, which have very similar geometries as those in crystalline **2**, are obviously forced by stereochemistry, and cannot be avoided by ring inversion. In retrospect, we interpret these contacts analogously as those in the *O*-substituted cyclohexanes: they are not hydrogen bonds, but they are not unfavourable either.

Conclusions

The above observations show that in substituted cyclohexanes, O and N atoms in axial position lead only to small distortions of the cyclohexane ring, much smaller than the distortions caused by C- or Br-substituents. In consequence, the conformation with axial O (or N) substituent is only weakly disfavoured over the one with equatorial substituent. In crystal structures, the less favourable conformers are therefore relatively frequently observed.

We interpret these observations by intramolecular interactions of the axial O-atom with the axial H-atoms of the cyclohexane ring, which allow intramolecular contacts to become relatively short without causing much strain. However, it must be stressed that the O-atom is still weakly repelled by the axial H-atoms, and the interpretation of these contacts as 'hydrogen bonds' is inadequate. For axial C-substituents, no such strain-relieving mechanisms exist.

In the whole, the situation is very subtle: the discussed C–H · · · O interactions make an unfavourable situation less unfavourable, they relieve steric strain, but the point is not reached where the situation would become energetically favourable.

Experimental

Crystallography

β-Cyclodextrin–*trans*-cyclohexane-1,4-diol·5.4H$_2$O(compound 1). Slow cooling (Dewar flask) of concentrated aqueous solutions of β-CD (Sigma) with a large molar excess (1 : 10 and more) of *cis*/*trans*-1,4-cyclohexanediol (Lancester) from 70 °C to room temp. yields colourless prismatic crystals of composition β-CD–*trans*-1,4-cyclohexanediol·5.4H$_2$O, $C_{42}H_{70}O_{35}$·$C_6H_{12}O_2$·5.4H$_2$O, $M = 1346.4$. To prevent dehydration, the crystal used for X-ray data collection (dimension 0.4 × 0.2 × 0.2 mm) was mounted in a glass capillary together with some mother liquor. The space group is monoclinic $P2_1$ (No. 4), with unit cell dimensions $a = 20.042(6)$, $b = 10.378(2)$, $c = 15.123(9)$ Å, $\beta = 102.30(2)°$, $V = 3073(2)$ Å^3; $Z = 2$, $Z' = 1$, $D_c = 1.457$ g cm^{-3}. Intensities of 4497 reflections were measured, 3271 of which are independent, 3027 with $I > 2\sigma(I)$ (Enraf–Nonius Turbo-CAD-4 diffractometer, FR571 rotating anode X-ray generator, Ni-filtered Cu-Kα-radiation with $\lambda = 1.5418$ Å, room temperature). The packing of the β-CD host molecules is isostructural with that in the crystalline complex β-CD–hexamethylenetetramine hexahydrate,[24] so that the atomic coordinates of the latter were used for initial phasing. Structure refinement was performed with standard methods[25] (H-atoms bonded to C calculated in ideal positions, water and hydroxy H-atoms not located, three β-CD primary hydroxy groups twofold disordered, seven distinct water sites with a sum of occupancy of 5.4). The cyclohexane and water guest molecules exhibit large thermal vibrations, as is not unusual for cyclodextrin inclusion complexes (ref. 1, and references cited therein).

Therefore, the covalent bond lengths and angles of the cyclohexane ring were restrained to ideal values in refinement. In consequence, also the geometry of the host–guest interactions is less reliably determined as in typical small molecule crystal structures, and is therefore not discussed in detail above. Furthermore, we should note that with crystallographic methods, impurities below *ca.* 5% cannot be detected. In consequence, it might be possible that a small fraction of the β-CD molecules in the crystal lattice host actually not the *trans*, but the *cis*-isomer of cyclohexane-1,4-diol. Refinement converged with $R = 0.068$ for the observed reflections.

***trans*-Cyclohexane-1,4-diol (compound 2).** Slow evaporation of EtOH solution of *cis*/*trans*-cyclohexane-1,4-diol (Lancester) yields a large bulk of precipitate and some additional small prismatic crystals which are composed of the pure *trans* isomer, $C_6H_{12}O_2$, $M = 116.16$. The space group is monoclinic $P2_1/n$ (No. 14) and unit cell dimensions are $a = 6.360(1)$, $b = 21.260(7)$, $c = 7.302(2)$ Å, $\beta = 95.93(2)°$, $V = 982.0(4)$ Å^3; $Z = 6$, $Z' = 1.5$, $D_c = 1.178$ g cm^{-3}. A crystal with dimensions 0.30 × 0.07 × 0.07 mm was glued to a glass fibre and used for the X-ray experiments on the same equipment as for **1**. Intensity data of 1824 reflections were measured, 1454 of which are independent, 1072 with $I > 2\sigma(I)$. The structure was solved with direct methods[26] and refined with standard procedures[25] (H-atoms bonded to C refined in the riding model, H-atoms bonded to O refined isotropically). Refinement converged with $R = 0.034$ (for observed reflections).

Full crystallographic details of **1** and **2**, excluding structure factor tables, have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, available *via* the RSC Web pages (http://chemistry.rsc.org/rsc/p1pifa.htm). Any request to the CCDC for this material should quote the full literature citation and the reference number 188/111.

Database analysis

All database searches were performed using the June 1997 update of the Cambridge Structural Database[3] (CSD) with 167 797 entries. Retrieved were organic and organometallic crystal structures with crystallographic *R*-values <0.10. Since the main interest was in the overall conformation of cyclohexane moieties, and not on fine structural details, it is justified to use such a permissive quality criterion.

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References

1 For recent contributions, see: Th. Steiner, A. M. Moreira da Silva, J. J. C. Teixeira-Dias, J. Müller and W. Saenger, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 1452; Th. Steiner and W. Saenger, *J. Chem. Soc., Chem. Commun.*, 1995, 2087; Th. Steiner, F. Hirayama and W. Saenger, *Carbohydr. Res.*, 1996, **296**, 83; A. Moreira da Silva, Th. Steiner, W. Saenger, J. Empis and J. J. C. Teixeira-Dias, *Chem. Commun.*, 1997, 465; Th. Steiner and W. Saenger, *Acta Crystallogr., Sect. B*, in the press.

2 Th. Steiner, *Chem. Commun.*, 1997, 727; G. R. Desiraju, *Acc. Chem. Res.*, 1996, **29**, 441.

3 F. H. Allen and O. Kennard, *Chem. Des. Autom. News*, 1993, **8**, 1.

4 F. Brisse and A. Palmer, *Acta Crystallogr., Sect. B*, 1982, **38**, 211.

5 B. Remillard and F. Brisse, *Acta Crystallogr., Sect. B*, 1982, **38**, 1220.

6 T. M. Lane, D. S. Grubisha, C. Hu and D. W. Bennett, *J. Mol. Struct.*, 1994, **328**, 133.

7 J. L. Stark, A. L. Rheingold and E. A. Maatta, *J. Chem. Soc., Chem. Commun.*, 1995, 1165.

8 P. Schönholzer, D. Suss, T. S. Wan and A. Fischli, *Helv. Chim. Acta*, 1984, **67**, 669.

9 P. G. Jones, A. J. Kirby and J. K. Parker, *Acta Crystallogr., Sect. C.*, 1992, **48**, 849.

10 J. M. White and G. B. Robertson, *Acta Crystallogr., Sect. C*, 1993, **49**, 347.

11 U. Rychlewska, M. B. H. Broom and D. J. Hodgson, *Acta Crystallogr., Sect. C*, 1984, **40**, 1004.

12 E. Juaristi, B. Gordillo, R. Martinez and R. Toscano, *J. Org. Chem.*, 1989, **54**, 5963.

13 H. Wunderlich and D. Mootz, *Acta Crystallogr., Sect. B*, 1971, **27**, 2437.

14 P. van Roey, K. A. Bullion, Y. Osawa, R. M. Bowman and D. G. Braun, *Acta Crystallogr., Sect. C*, 1991, **47**, 1015.

15 R. Friedrich, M. Nieger and F. Vögtle, *Chem. Ber.*, 1993, **126**, 1723.

16 R. Krieg, H.-J. Deutscher, U. Baumeister, H. Hartung and M. Jaskolski, *Mol. Cryst. Liq. Cryst.*, 1989, **109**, 166.

17 G. Echeverria, G. Punte, B. E. Rivero and M. Baron, *Acta Crystallogr., Sect. C*, 1995, **51**, 1020.

18 E. Juaristi, N. A. Lopez-Nunez, B. A. Valenzuela, L. Valle, R. A. Toscano and M. Soriano-Garcia, *J. Org. Chem.*, 1987, **52**, 5185.

19 M. A. Chisholm, C. E. Hammond and J. C. Huffman, *Polyhedron*, 1989, **8**, 129.

20 G. Siasios and E. R. T. Tiekink, *Z. Kristallogr.*, 1993, **204**, 95.

21 J. S. Casas, A. Castineiras, M. S. Garcia-Tasende, A. Sanchez, J. Sordo and E. M. Vasquez-Lopez, *Polyhedron*, 1995, **14**, 2055.

22 A. Bondi, *J. Phys. Chem.*, 1964, **68**, 441.

23 Th. Steiner and W. Saenger, *J. Am. Chem. Soc.*, 1992, **114**, 10 146.

24 K. Harata, *Bull. Chem. Soc. Jpn.*, 1984, **57**, 2596.

25 G. M. Sheldrick, SHELXL-93, *Program for the Refinement of Crystal Structures*, University of Göttingen, Germany, 1993.

26 Sheldrick, C. Krüger and R. Goddard, Oxford University Press, pp. 175–189.

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