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Structure of the uncharged, anionic, and cationic forms of aminoalkylcarboxylic and aminoalkylphosphonic complexones

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ABSTRACT. This review is concerned with an analysis of the structure of aminocarboxylic and aminophosphonic acids from the data of X-ray diffraction studies. Monoamino and diamino (also triamino) complexones, the prototropic tautomerism of complexones, and the structural characteristics of their hydrohalides are examined successively.

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I. Introduction

In 1936 the company "IG Farbenindustrie" started the manufacture of two products used as water softening agents—Trilon A (nitrilotriacetic acid) and Trilon B (the disodium salt of ethylenediaminetetraacetic acid). These were the first complexones. However, complexones only gained wide acceptance at the end of the 1940s and beginning of the 1950s when their use as complexometric titrating agents for the approximate analysis of virtually all metal cations and many anions was proposed, which gave rise to the current revolution in analytical chemistry.

Schwarzenbach, Kampitsch, and Steiner[1] proposed the term "complexone". Originally it was only applied to polyaminopolycarboxylic acids that have a well-defined tendency to undergo polydentate coordination with metals.

At the present time the term "complexone" refers not only to polyaminopolycarboxylic acids ("classical" complexones) but also to compounds that combine any other basic (S and P atoms, $\rangle C-H$ or $\rangle C-N\langle$ groups) and acidic (phosphonic, arsonic, or sulphonic) sites ("modified" complexones).

In this review only aminocarboxylic and aminophosphonic complexones, whose structure has been studied much more extensively than the structure of other classes of complexones, will be examined. Replacement of carboxyl groups of methylphosphonic groups leads to considerable changes in not only the properties but also the stereochemistry of these compounds. Nevertheless, in the structure of complexones that differ in composition certain common features are retained in many cases, and the present review is to a greater extent devoted to identifying these features. From this point of view there is a discussion of intra- and inter-molecular hydrogen bonds, which play a significant role in the crystal chemistry of all complexones.

During the last ten years the practical application of complexones has extended far beyond the limits of analytical chemistry. They are used anywhere where it is necessary to eliminate the deleterious effect of a metal or, conversely, to introduce a metal into a given system—in the chemical, gas, or petroleum industries, in electrolytic metallurgy, the film industry, power engineering, building, applied bioinorganics, the food industry, agriculture, and in medicine.

The main characteristics of complexones as ligands, making them effective in binding cations and as a result giving rise to their wide popularity in so many different areas, lies in their combination of flexibility and given geometric limitations in coordination, which differ according to the composition of the complexone. The strength of the complexes formed by them is determined, on the one hand, by the considerable covalent nature of the bonds with the metal (namely, by the nature of the active sites of the complexone together with the electronic structure of the metal), and on the other hand by the complementarity of the ligand shape of the complexone with the corresponding cation, i.e., a purely geometric factor. This latter circumstance dictates the importance of studying the stereochemistry of complexones (also metal complexonates).

In the USSR studies on the synthesis of complexones and metal complexonates were started in the 1950s and their systematic structural analysis was initiated in about 1970 [by the group led by T N Polynova at the Chemistry Department of Moscow State University together with the Institute of General and Inorganic Chemistry, USSR Academy of Sciences and by L M Shkol'nikova's group at the All-Union Scientific-Research Institute of Chemical Reagents and Specially Pure Chemicals (VNII IREA)].

On the whole, the structural data on metal complexonates are considerably more abundant than that for complexones themselves. However, even the latter include more than 50 structural studies (two thirds of which have been carried out in the USSR), so that an examination of the results of these studies on the basis of a single approach is now suitable and timely.

The name and standard notation of the aminocarboxylic and aminophosphonic complexes studied are given in Table 1. References to the original X-ray diffraction studies of these compounds are also given there.

Table 1. List of complexones studied.

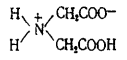
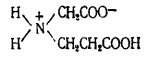
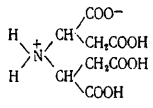
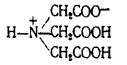
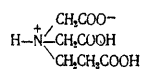
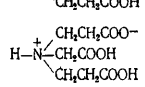
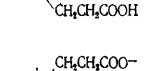
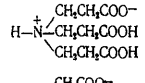
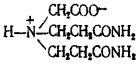
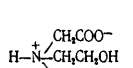
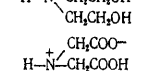
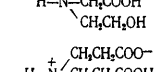
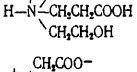
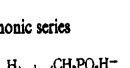
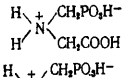
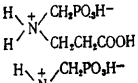
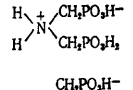
Name of compound	Standard notation	Structural formula	Refs.
Monoaminoalkylcarboxylic series			
Iminodiacetic acid	H_2ida		[2, 3]
Glycinopropionic acid dihydrate	$H_2gp \cdot 2H_2O$		[4]
Iminodisuccinic acid monohydrate	$H_4ids \cdot H_2O$		[5]
Nitrilotriacetic acid	H_3nta		[6]
Nitrilopropionic diacetic acid	H_3npda		[4]
Nitrilodipropionic acetic acid	H_3ndpa		[4]
Nitrilotripropionic acid	H_3ntp		[7]
Nitrilodipropionamidomonoacetic acid	$Hndpma$		[8]
Diethanolglycine	$Hdeg$		[9]
β-Hydroxyethyliminodiacetic acid	$\beta\text{-}H_3heida$		[10]
β-Hydroxyethyliminodipropionic acid	$\beta\text{-}H_3heidp$		[11]
Mercaptoethylaminotriacetic acid monohydrate	$H_3meata \times H_2O$		[12]
Methyliminodiacetic acid	H_2mida		[13]
Monoaminoalkylphosphonic series			
Phosphonomethylglycine	H_5phmg		[14]
Phosphonomethylalanine	H_5phma		[15]
Iminodimethylphosphonic acid	H_4idph		[16]
Phosphonomethyliminodiacetic acid	$H_4phmida$		[14]
Glycinodimethyl phosphonic acid dihydrate	$H_5gdph \times 2H_2O$		[15]

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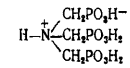
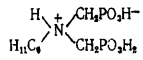
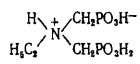
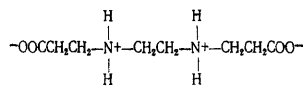
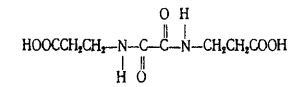
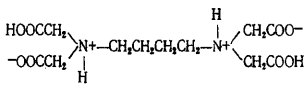
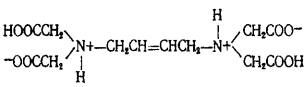
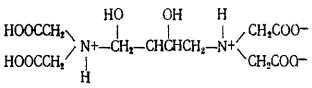
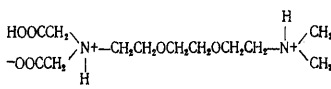
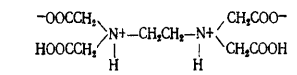
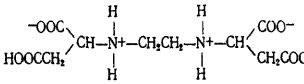
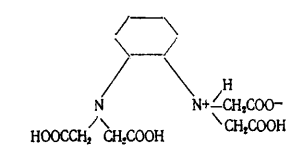
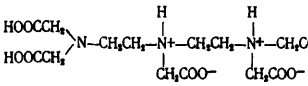
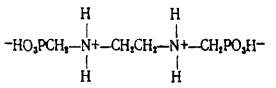
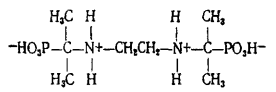
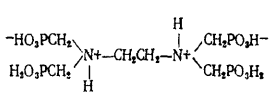
Name of compound	Standard notation	Structural formula	Refs.
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Nitrilotrimethyl phosphonic acid	H_6ntph		[17]
Cyclohexyliminodimethyl phosphonic acid	H_4cidph		[16]
Ethylaminodimethyl phosphonic acid	H_4eadph		[18]
Diaminoalkylcarboxylic series			
Ethylenediamine-*N,N'*-dipropionic acid dihydrate	$H_2eddp \times 2H_2O$		[4]
Oxamido-*N,N'*-dipropionic acid	H_2oadp		[19]
1,4-Butanediamine-*N,N,N',N'*-tetraacetic acid dihydrate	$H_4dbata \times 2H_2O$		[4]
1,4-Butenediamine-*N,N,N',N'*-tetraacetic acid dihydrate	$H_4dbeta \times 2H_2O$		[4]
2,3-Dihydroxy-1,4-butanediamine-*N,N,N',N'*-tetraacetic acid dihydrate	$H_4dhobta \times 2H_2O$		[20]
Ethylenebis(oxyethylenenitrilo) tetraacetic acid	H_4egta		[21]
Ethylenediamine-*N,N,N',N'*-tetraacetic acid	H_4edta		[22—24]
Ethylenediamine-*N,N'*-disuccinic acid pentahydrate	$H_4edds \cdot 5H_2O$		[25]
trans-1,2-Cyclohexanediamine-*N,N,N',N'*-tetraacetic acid monohydrate	$H_4cdta \cdot H_2O$		[26, 27]
Triaminoalkylcarboxylic series			
Diethylenetriamine-*N,N,N',N'',N''*-pentaacetic acid	H_5dtpa		[26, 28]

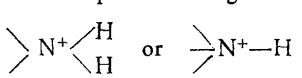
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Name of compound	Standard notation	Structural formula	Refs.
		Diaminoalkylphosphonic series	
Ethylenediamine-*N,N'*-dimethylphosphonic acid dihydrate	H_4eddph×$\times 2H_2O$		[29]
Ethylenediamine-*N,N'*-diisopropylphosphonic acid dihydrate	H_4eddiph×$\times 2H_2O$		[29]
Ethylenediamine-*N,N,N',N'*-tetramethylphosphonic acid monohydrate	H_8edtph		[30]

II. Main structural features of complexones

One of the general problems to be resolved from X-ray diffraction studies on the crystals of compounds that can in principle exist in different forms is the establishment of a correlation between the structure of individual molecules or molecular ions in solution (determined from a combination of physicochemical properties) and their structure in crystals, namely, under conditions of direct and constant contact in time and space between the structural units. This problem relates particularly to the determination of the structural role of separate functional groups of complex molecules under different conditions.

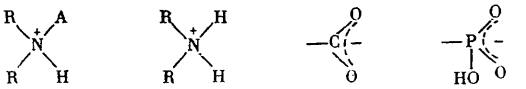
As far as complexones are concerned, there is first of all the question as to the predominant tautomeric form of the molecules. It is known that in aqueous solution complexones, as a rule, have a betaine structure with the positive charge on ammonium centres



(quaternised nitrogen) and the negative charge on one of the acid groups (deprotonated acid group).

Is this type of structure retained in crystals, where the tendency to form a system of N—H...O or O—H...O intermolecular hydrogen bonds can lead to tautomeric rearrangement? What is the relationship between intramolecular and intermolecular hydrogen bonding in a crystal? Would it be possible, despite the individual nature of the crystalline structure of each compound, to establish a general basis for the conformation of complexone molecules and hence to determine experimentally (without calculations) which molecular forms are the most stable? These were the main questions that were raised and resolved in a series of structural studies on complexones carried out at VNII IREA.

An analysis of the results of structural studies on about forty complexones based on mono-, di-, and tri-amines showed that their zwitterion structure is retained in the crystalline state. The molecules contain positively charged ammonium centres (A) or (B) and negatively charged acidic centres (C) or (D) (carboxylate or phosphonate):



(A) (B) (C) (D)

By studying the structure of molecules containing different functional groups, it was possible to establish which of the groups is most susceptible to deprotonation under competitive conditions. Naturally, the group with a higher acidity was deprotonated in all cases. In an IR spectroscopic study of phosphonomethyliminodiacetic acid (H_4phmida) in solution and its deuterium derivative in the solid state[31] it was shown that a zwitterion structure occurs via a proton from the methylphosphonic group rather than a competing acetate group. A study of crystals of H_4phmida and phosphonomethylglycine (H_3phmg) confirmed this result. It was established that in glycinopropionic (H_2gp) and nitrilopropionic diacetic (H_3npda) acids, namely, when acetate and propionate groups are present, the acetate group is deprotonated; in diethanolglycine (Hdeg) and β-hydroxyethyliminodiacetic acid (β-H_2heida) where acetate and β-hydroxyethyl groups are present, the acetate group is deprotonated; in β-hydroxyethyliminodipropionic acid (β-H_2heidp) where β-hydroxyethyl and propionate groups are present, the propionate group is deprotonated; and in iminodisuccinic acid (H_4ids), the more acidic α-carboxyl group rather than the β-carboxyl group is deprotonated. The only exception is nitrilodipropionic acetic acid (H_3ndpa), where a propionate group was found to be deprotonated when an acetate group was present. The explanation of this violation of the general rule is given below. Consequently, the functional groups can be arranged in a series representing a decreasing tendency to undergo deprotonation during competition between acidic groups (for complexones containing different functional groups:

$$CH_2PO_3H_2 > CH_2COOH > CH_2CH_2COOH > CH_2CH_2OH.$$

Thus, in all of the complexones where there are not less than two carboxyl groups per N atom, one of them is always present in the form of a deprotonated carboxylate group (C) (in the absence, of course, of the more active phosphonic group). Similarly in complexes containing not less than two diprotonated phosphonic groups $P(O)(OH)_2$ per N atom, one of them always occurs in the form of a monoprotonated (phosphonate) group (D).

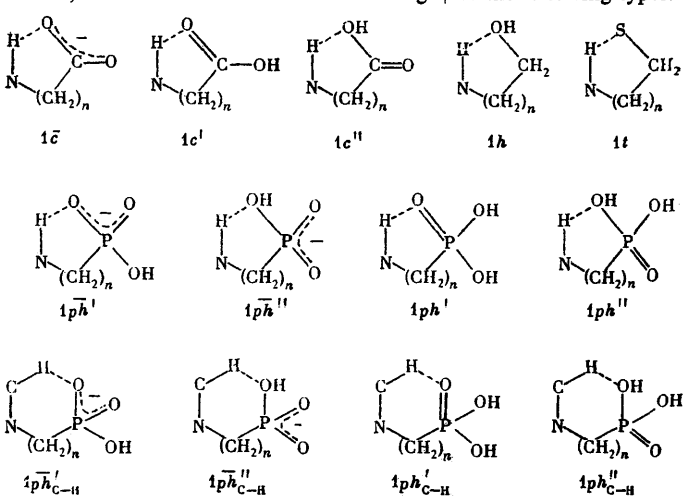
Only in oxamido-*N,N'*-di-3-proprionic acid (H_2oadp) is the betaine structure absent. Nevertheless, even for this compound the formation of intramolecular N—H...O hydrogen bonds is typical (here H is a non-betaine hydrogen atom).

Since the first structurally investigated diaminocarboxylic complexes—H_4edta and H_4edds·$5H_2O$—had a symmetric bis-zwitterion structure with two quaternised N atoms and two deprotonated carboxyl groups, such a structure was also assumed for other diaminocarboxylic complexes for a long time. However, in a study of the structure of H_4cdta an asymmetric betaine structure of the molecule with only one quaternised N atom was found. The presence of another tautomer with a symmetric structure appears to be possible in solution. Incomplete quaternisation of the N atoms (two out of three) was also found in the molecule of the only structurally investigated triaminocarboxylic complexone—H_5dtpa. Incomplete quaternisation of the N atoms does not occur in the structurally investigated diaminophosphonic

complexones, which is probably due to the increased acidity of the phosphonic group compared to the carboxyl group.

The presence of a quaternised nitrogen atom and negatively charged oxygen atoms of acidic groups in complexones increases their tendency to form hydrogen bonds of the type N–H...O. These hydrogen bonds may be both intramolecular (IAHB) and intermolecular (IEHB) and together with other H-bonds they determine the overall molecular conformation, which depends in the long run on the kinetic and thermodynamic advantage for formation of a given system of hydrogen bonding during crystallisation of an acid.

The structural studies carried out indicate that complexone molecules of both monoamino and diamino types always form N–H...O intramolecular hydrogen bonds in addition to intermolecular hydrogen bonds of the type O–H...O and N–H...O, with the N–H group usually participating in IAHB simultaneously with two or three oxygen atoms, i.e., it forms bi- or tri-furcated H-bonds. As an example, the molecule of iminodisuccinic acid (H_4ids) is shown in Fig. 1. Both ammonium hydrogen atoms form bifurcated IAHB, and one of them also participates in IEHB, so that as a whole the H-bond of this N–H group becomes trifurcated. The presence of intramolecular H-rings based on N–H...X hydrogen bonds is one of the most characteristic features of the structure of complexones.[32] The most commonly occurring of them are rings that each contain one nitrogen atom. Amongst the complexes covered in the present review, are to be found mononitrilo-H-rings † of the following types:



† Several different systems of nomenclature for normal H-rings in complexones have already been put forward.[28,33,34] In order to increase their informative capacity and clarity, a new system is proposed in this review: the numeral 1 (as in the studies of Shkol'nikova et al.[28,33]) denotes that only one N atom participates in the formation of an H-ring (we will also consider below rings involving two N atoms, which will be labelled with the numeral 2); *c* denotes carboxylate; *h* is hydroxyethyl; *ph* is phosphonate; *t* is thio; ph_{C-H} is phosphonate with a C–H...O bond. A minus sign above the letters ($\bar{c}$, $\overline{ph}$) is an indication of an ionised group, a single prime against the letter (e.g., *c′*, $\overline{ph}'$) is an indication that a hydrogen bond is formed via the terminal O atom) and a double prime (e.g. *c″*, $\overline{ph}''$) is an indication of hydrogen bonding via the hydroxyl O atom as a hydrogen acceptor. The presence of a $(CH_2)_2$ group instead of CH_2 is recorded using a subscript 2 (e.g. $1\bar{c}_2$, see below).

The first three H-rings ($1\bar{c}$, 1*c′*, 1*c″*) are nitrilocarboxylic, the fourth (1*h*) is nitrilohydroxyethyl, the fifth (1*t*) (a special case) is analogous to the first, when an O atom is replaced by the heteroatom S. The following four H-rings (second row) are nitriloalkylphosphonic, and the last four are rarely encountered nitrilophosphonic rings with weak C–H...O hydrogen bonding. The rings $1\bar{c}$, $1\overline{ph}'$, $1\overline{ph}''$, $1\overline{ph}_{C-H}'$, and $1\overline{ph}_{C-H}''$ include deprotonated (ionised) acidic groups, the remaining rings involve protonated (formally neutral) groups. They differ from each other according to the nature of the oxygen atom participating in IAHB (while in the rings $1ph_{C-H}'$, and $1ph_{C-H}''$ they differ according to the nature of the proton donor atom). The $(CH_2)_n$ alkyl chain most frequently contains one unit (n = 1), with two units (n = 2) being less frequent.

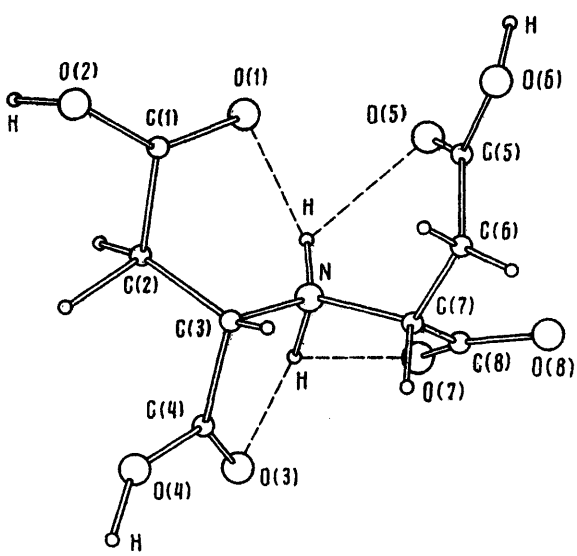


Figure 1. Structure of the iminodisuccinic acid (H_4ids) molecule.

Typical forms of H-ring that include two nitrogen atoms are examined below when the structure of di- and tri-amino complexones is discussed.

The combinations of H-rings in complexone molecules can vary considerably according to the composition of the complexone. Nevertheless, we can consider several quite standard combinations (sets) of H-rings that recur in different compounds. This is especially typical for combinations of five-membered H-rings. As a rule, five-membered H-rings have an envelope conformation, with dihedral angles between the rings lying within the comparatively narrow region of 90–130°. In this respect a clear genetic relationship can be traced between the stereochemistry of mono-, di- and tri-amino complexones.

III. Structure of monoamino complexones

Monoamino complexones can be divided into two groups in accordance with the structural nature of the central ammonium site: complexones with two H atoms on quaternised N (H_2ida class) and complexones with a single hydrogen atom on the betaine unit (H_3nta class).

In the first case, each of the two ammonium protons forms its (or their) independent H-ring, in the second case the H-rings are joined together by a common N–H bond.

The first group, in addition to the three forms of iminodiacetic acid (H_2ida), also includes H_2gp·$2H_2O$, H_3phmg, H_4idph, and H_4ids·H_2O (for labelling of the acids, see Table 1). The remaining 12 monoamino acids studied, including H_3nta itself, belong to the second group.

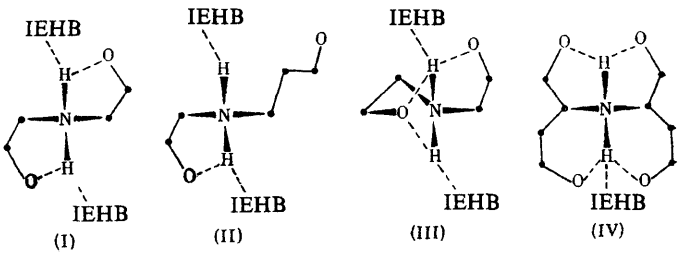
It is clear from the data given in Table 2 that in complexones of the H_2ida class the intramolecular H-bonds are considerably weaker than in complexones of the H_3nta class. This is especially apparent when comparing molecules that are similar in composition. In H_2ida the lengths of the intramolecular H...O bonds in all three modified forms is in the region 2.37–2.63 Å (the exception to this is one H-bond in the A form, where this distance is reduced to 2.16 Å), while in H_3nta the lengths are in the region 2.14–2.26 Å. In the glycinopropionic acid molecule (H_2gp) it is equal to 2.40 Å while in nitrilopropionic diacetic acid (H_3npda) the lengths are 2.13 and 2.27 Å. In H_3phmg the H...O distance to the O atom of the carboxyl group is 2.59 Å whereas in H_4phmida the distances are 2.38 and 2.44 Å and in H_5gdph it is 2.38 Å.‡

It also follows from the data given in Table 2 that the reduced length of the IAHB of the type N–H...O–C on going from H_2ida class complexones to H_3nta class complexones does not depend very much on the nature of the substituents R replacing the second hydrogen atom on nitrogen. Consequently, the cause of the weakening in IAHB in complexones of the first group is the very fact of increasing the number of hydrogen atoms on N. This, firstly, reduces their capacity to interact with O atoms and, secondly, increases the competitive capacity of intermolecular H-bonds, which are less rigidly restricted by the N–H...O angle. As the data of Table 2 also indicate, IEHB is much stronger than IAHB in all cases.

It is somewhat different picture with hydrogen bonding in which oxygen atoms of phosphonic or phosphonate groups participate. In this case the differences in strength of IAHB caused by the different degree of protonation of N atoms disappear, since IAHB of the type N–H...O–P is nearly always much weaker than IAHB of the type N–H...O–C.

a) Complexones of the iminodiacetic acid (H_2ida) class

Amongst the structures of monoaminocarboxylic complexones of the H_2ida class that were studied, four different combinations of IAHB and IEHB occur:



(I) (II) (III) (IV)

The structure of the H_2ida molecule in its two crystalline forms A and C is of a single type; each H forms a single H-ring and one IEHB [scheme (I)]. A similar combination occurs in the two monoaminophosphonic complexones H_3phmg and H_4idph. Replacement of the protonated acetate group by a protonated propionate group on going from H_2ida to H_2gp.$2H_2O$ (and on going from H_3phmg to H_3phma) causes the corresponding IAHB to disappear [scheme (II)]. Studies on other complexones and their cationic forms containing protonated propionate groups showed that H-rings of the type $1c'_2$ which are feasible in H_2gp and H_3phma are only formed when they are joined to other H-rings, and not in all cases (see below), whereas H-rings of the type $1c''_2$ are not formed at all.

In the two crystallographically independent H_2ida molecules with a stable B form, labelled B′ and B″ in Table 2, the formation of uniform sets of hydrogen bonds was detected, as shown in scheme (III). A characteristic of the system of hydrogen bonds here is the joining up of the $1c''$ H-rings along the line of O–C–C–N since the acceptor of IAHB that completes these rings is one and the same hydroxyl O atom of the carboxyl group.

On the whole the H...P distances (IAHB) in this class of aminocarboxylic complexones are in the range 2.37–2.63 Å and the angles at the H atoms are in the range 85–102°. Both these results indicate the weakness of such hydrogen bonds. An exception to this is one of the IAHB in the A form of H_2ida, where the H...O distance is equal to 2.16 Å and the N–H...O angle is 114°. Even less distinct are H-rings involving methylphosphonic groups. Many of them can only be regarded as hypothetical since the H...O distances in them are great as 2.60–2.80 Å, while in H_4cidph even 2.92 Å is attained.

In cyclohexyliminodimethylphosphonic acid (H_4cidph), in addition to a five-membered ring it is also possible to detect a six-membered H-ring (based on a C–H...O bond) of the type $1ph''_{C-H}$, in which the H...O distance is 2.46 Å and the C–H...O angle is 133°. In iminodimethylphosphonic acid a ring of the type $1ph'_{C-H}$ is more representative—the distance is 2.60 Å and angle is 122° (for more details about C–H...O bonds, see below). Naturally, intermolecular hydrogen bonding is much stronger in these compounds than IAHB; the H...O distances are in the range 1.80–2.01 Å (in H_4idph they are 2.12 Å) and the angles at the H atoms increase to 150–180°.

‡ It is assumed that the low accuracy in establishing the position of hydrogen atoms and the variable level of accuracy in structural studies result in a comparison of specific individual distances and angles involving hydrogen atoms not being entirely correct. Therefore, in this case and later in the text we shall examine only general trends that are sufficiently apparent without being dependent on the accuracy of individual figures.

It should be mentioned here that we recognise the actual concept of intramolecular hydrogen bonding to a sufficient extent hypothetically, without limiting the upper limits of the H...O or N...O distances to any specific value (for example, the sum of the van der Waals radii with an additional margin of 0.2 Å). The main criterion for the present authors is the degree of deviation of the C–O (or P–O) bond from the average planarity of the H-ring being formed. We consider that a hydrogen bond actually exists if on the whole the C–O (P–O) bond "faces" towards the ammonium centre of the complexone.

Table 2. Geometric properties of N–H...O hydrogen bonds in the structures of monoaminocarboxylic and monoaminophosphonic complexones.

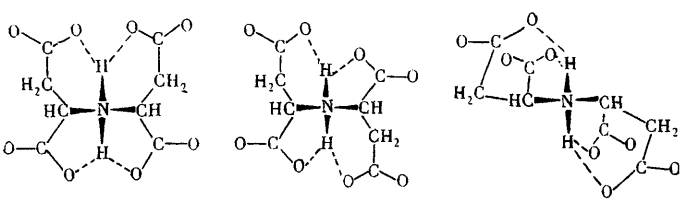
Complexone	Labelling of H-ring or IEHB	Geometry of N–H...O bond				Sets of H-bonds	Angle between rings, deg
		Distance, Å			N–H...O angle, deg		
		N–H	H ..O	N...O			
$H_2ida(A)$	$1\bar{c}$	0.93 (2)	2.16 (3)	2.675 (2)	114 (2)	$1\bar{c}$-IEHB	
	IEHB	0.93 (2)	1.99 (2)	2.674 (2)	149 (2)		
	$1\bar{c}$	0.93 (3)	2.63 (3)	2.733 (2)	86 (2)	$1c'$-IEHB	
	IEHB	0.93 (2)	1.96 (3)	2.807 (2)	151 (2)		
$H_2ida(B')$	$1\bar{c}$	1.10 (6)	2.52 (5)	2.652 (6)	85 (6)	$1\bar{c}$-$1c''$-IEHB	
	$1c''$	1.10 (6)	2.37 (6)	2.657 (6)	93 (5)		
	IEHB	1.10 (6)	1.80 (6)	2.880 (7)	163 (6)		
	$1c''$	0.77 (6)	2.39 (5)	2.657 (6)	102 (6)	$1c''$-IEHB	
	IEHB	0.77 (6)	2.00 (6)	2.750 (5)	161 (5)		
$H_2ida(B'')$	$1\bar{c}$	0.93 (6)	2.60 (6)	2.675 (5)	84 (5)		
	$1c''$	0.93 (6)	2.58 (6)	2.669 (5)	85 (6)	$1\bar{c}$-$1c''$-IEHB	
	IEHB	0.93 (6)	1.90 (6)	2.840 (6)	180 (6)		
	$1c''$	0.86 (6)	2.49 (6)	2.669 (5)	93 (6)	$1c''$-IEHB	
	IEHB	0.86 (6)	2.00 (5)	2.750 (5)	161 (6)		
$H_2ida(C)$	$1\bar{c}$	0.95 (3)	2.45 (4)	2.664 (3)	92 (3)	$1\bar{c}$-IEHB	
	IEHB	0.95 (3)	1.91 (4)	2.812 (3)	157 (3)		
	$1c'$	0.98 (3)	2.44 (4)	2.698 (3)	95 (3)	$1c'$-IEHB	
	IEHB	0.98 (3)	1.81 (3)	2.781 (3)	171 (3)		
$H_2gp \cdot 2H_2O$	$1\bar{c}$	0.80 (6)	2.40 (6)	2.631 (5)	98 (4)	$1\bar{c}$-IEHB	
	IEHB	0.80 (6)	2.01 (6)	2.781 (5)	163 (5)		
	IEHB	1.02 (6)	1.87 (6)	2.813 (6)	153 (5)	IEHB	
$H_4ids \cdot H_2O$	$1\bar{c}$	1.10 (10)	2.02 (10)	2.629 (12)	110 (6)	$1\bar{c}$-$1c'$	108
	$1c'$	1.10 (10)	2.14 (9)	2.623 (11)	102 (6)		
	$1c_2'$	0.89 (8)	2.50 (8)	2.896 (11)	108 (6)		
	$1c_2'$	0.89 (8)	2.39 (8)	2.965 (10)	123 (6)	$1c_2'$-$1c_2'$-IEHB	113
	IEHB	0.89 (8)	2.33 (8)	3.087 (10)	143 (7)		
H_2ids^{2-}	$1\bar{c}$	1.06	2.31	2.69 (1)	99	$1\bar{c}$-$1\bar{c}$	120
in $[Cu(H_2ids)(dipy)_2]$	$1\bar{c}$	1.06	2.06	2.68 (4)	115		
fum.$5H_2O$ (Ref.35)	$1\bar{c}_2$	0.96	1.97	2.70 (1)	131	$1\bar{c}_2$-$1c_2'$	105
	$1c_2'$	0.96	2.29	2.92 (1)	130		
H_3nta	$1\bar{c}$		2.14	2.63		$1\bar{c}$-$1c'$	111
	$1c'$		2.26	2.68			
$Hnta^{2-}$	$1\bar{c}$	0.91	2.26	2.769	115		104
in [Ca(Hnta)].$2H_2O$P (Ref.36)	$1\bar{c}$	0.91	2.29	2.670	105	$1\bar{c}$-$1\bar{c}$-$1\bar{c}$	108
	$1\bar{c}$	0.91	2.35	2.702	103		98
$Hnta^{2-}$	$1\bar{c}$	1.03	2.10	2.539	103		
in Na[Na(Hnta)] (Ref.37)	$1\bar{c}$	1.03	2.10	2.539	103	$1\bar{c}$-$1\bar{c}$-$1\bar{c}$	
	$1\bar{c}$	1.03	2.10	2.539	103		
H_2nta^-	$1\bar{c}$	0.95	2.35	2.69	100		
in $Ag(H_2nta)$ (Ref.38)	$1\bar{c}$	0.95	2.29	2.67	103	$1\bar{c}$-$1\bar{c}$-$1c'(c'')$	
	$1c'(1c'')$	0.95	2.48	2.78	98		
H_3npda	$1\bar{c}$	1.02 (4)	2.13 (4)	2.680 (4)	111 (3)	$1\bar{c}$-$1c'$-$1c_2'$	103
	$1c'$	1.02 (4)	2.27 (4)	2.736 (4)	106 (3)		93
	$1c_2'$	1.02 (4)	2.50 (4)	3.097 (4)	117 (3)		147
H_3ndpa	$1\bar{c}_2$	0.85 (7)	2.11 (7)	2.788 (7)	137 (6)	$1\bar{c}_2$-$1c'$	118
	$1c'$	0.85 (7)	2.23 (7)	2.658 (7)	111 (6)		
H_3ntp	$1\bar{c}_2$	1.02 (4)	2.11 (4)	2.803 (4)	123 (3)	$1\bar{c}_2$-$1c_2'$	109
	$1c_2'$	1.02 (4)	2.31 (4)	3.003 (4)	124 (3)		
Hndpma	$1\bar{c}$	0.92 (2)	2.13 (2)	2.669 (2)	116 (2)		90
	$1c_2'$	0.92 (2)	2.40 (2)	2.937 (2)	120 (2)	$1\bar{c}$-$1c_2'$-$1c_2'$	149
	$1c_2'$	0.92 (2)	2.37 (2)	3.001 (2)	127 (2)		114
Hdeg	$1\bar{c}$	0.85	2.19	2.670	116		111
	$1h$	0.85	2.31	2.743	112	$1\bar{c}$-$1h$-$1h$	119
	$1h$	0.85	2.31	2.738	111		115

Table 2 (cont'd).

Complexone	Labelling of H-ring or IEHB	Geometry of N–H...O bond				Sets of H-bonds	Angle between rings, deg
		Distance, Å			N–H...O angle, deg		
		N–H	H ..O	N...O			
β-H_2heida	$1\bar{c}$	0.84 (3)	2.27 (3)	2.654 (3)	100 (2)	$1c$-$1c''$-$1h$	91
	$1c''$	0.84 (3)	2.40 (3)	2.679 (3)	101 (2)		116
	$1h$	0.84 (3)	2.21 (2)	2.688 (4)	116 (2)		108
β-H_2heidp	$1\bar{c}_2$	0.93 (2)	2.12 (2)	2.826 (2)	132 (1)		120
β-H_2heidp	$1\bar{c}_2$	0.93 (2)	2.48 (2)	3.054 (2)	121 (1)	$1\bar{c}_2$-$1c'_2$-$1h$	107
	$1h$	0.93 (2)	2.61 (1)	2.998 (2)	105 (1)		116
H_3meata·H_2O	$1\bar{c}$	0.89 (3)	2.26 (3)	2.663 (3)	107 (3)	$1\bar{c}$-$1c'$-$1t$	111
	$1c'$	0.89 (3)	2.26 (3)	2.678 (3)	108 (3)		
	$1t$	0.89 (3)	2.61 (3)	3.139 (3)	119 (3)		
H_2mida	$1\bar{c}$	0.98 (2)	2.15 (2)	2.651 (2)	110 (2)		
	$1c'$	0.98 (2)	2.46 (2)	2.739 (2)	97 (1)	$1c$-$1c'$-IEHB	90
	IEHB	0.98 (2)	2.06 (2)	2.856 (2)	138 (2)		
H_3phmg	$1c'$	0.94 (2)	2.59 (2)	2.761 (1)	90 (1)	$1c'$-IEHB	
	IEHB	0.94 (2)	1.95 (2)	2.818 (1)	158 (2)		
	$1\overline{ph'}$	0.86 (2)	2.77 (2)	2.998 (1)	97 (2)	$1\overline{ph'}$-IEHB	
	IEHB	0.86 (2)	1.93 (2)	2.733 (1)	154 (2)		
H_3phmg in H_3phmg·½HCl (Ref.39)	$1c'$	0.86 (4)	2.46 (3)	2.665 (3)	93 (3)	$1c'$	
	IEHB	1.00 (4)	1.99 (3)	2.932 (3)	154 (3)	IEHB	
H_3phma	IEHB	0.93 (4)	1.99 (4)	2.932 (3)	173 (4)	IEHB-IEHB	
	IEHB	0.93 (4)	1.96 (4)	2.806 (3)	148 (4)		
H_4idph	$1ph''$	0.86 (5)	2.53 (5)	2.853 (4)	103 (3)	$1ph''$-IEHB	
	IEHB	0.86 (5)	2.12 (5)	2.884 (4)	149 (4)		
	$1\overline{ph'}$	0.84 (5)	2.77 (5)	2.968 (4)	95 (4)		
	IEHB	0.84 (5)	1.89 (3)	2.708 (4)	165 (5)	$1\overline{ph'}$-IEHB	
H_4phmida	$1c'$	0.85 (6)	2.38 (6)	2.737 (5)	106 (5)	$1c'$-$1c''$-IEHB	
	$1c''$	0.85 (6)	2.44 (6)	2.709 (5)	100 (5)		
	IEHB	0.85 (6)	1.99 (6)	2.763 (4)	151 (6)		
H_5gdph·$2H_2O$	$1c'$	1.09 (7)	2.38 (6)	2.732 (4)	96 (4)	$1c'$-$1\overline{ph'}$-IEHB	
	$1\overline{ph'}$	1.09 (7)	2.50 (6)	2.885 (4)	101 (4)		
	IEHB	1.09 (7)	1.84 (7)	2.892 (3)	159 (5)		
H_6nlph	$1\overline{ph'}$	0.94	2.66	3.160	114	$1\overline{ph'}$-$1ph'$-IEHB	
	$1ph'$	0.94	2.48	2.858	104		
	IEHB	0.94	2.02	2.842	144		
H_4cidph	$1\overline{ph'}$	0.79 (3)	2.80 (3)	3.077 (3)	103 (2)	$1\overline{ph'}$-$1ph'$-IEHB	
	$1ph'$	0.79 (3)	2.92 (3)	3.118 (2)	97 (2)		
	IEHB	0.79 (3)	1.91 (3)	2.697 (3)	171 (3)		
H_4eadph	$1ph''$	0.81 (8)	2.70 (9)	3.140 (4)	116 (8)	$1ph''$-IEHB	
	IEHB	0.81 (8)	2.07 (9)	2.810 (4)	152 (8)		

It is the weakness of IAHB (both relative and absolute) that leads to the stereochemical diversity of molecules of the H_2ida class. The molecules have a conformational flexibility and they readily change their conformation under the influence of IEHB. The existence of different crystalline forms of H_2ida is probably also a consequence of this.

Iminodisuccinic acid (H_4ids) can also formally be assigned to the H_2ida class [scheme (IV)]. The IAHB in it proved to be considerably stronger than in the remaining compounds of this class. The H_4ids molecule contains two succinate groups, which may be regarded as propionate groups with one of the H atoms replaced by a carboxyl group. It was established from X-ray diffraction studies that one of the α-carboxyl groups is deprotonated in accordance with its higher acidity compared to the β-group. In principle three ways of forming H-rings in H_4ids are possible, depending on the different combinations of IAHB involving the α- and β-carboxyl groups:



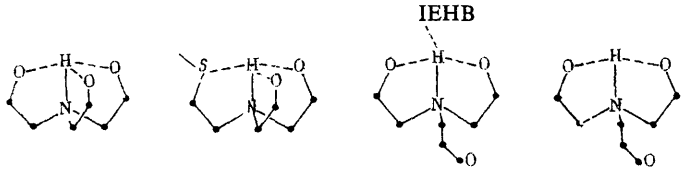
(A) (B) (C)

On crystallisation from solution, crystals in the form of (A) (Fig. 1) are isolated. The H_4ids molecule has a compact and probably the most favourable configuration energetically irrespective of intermolecular interactions, confirmation of which is its retention

in the structure of the heteroligand complex $[Cu(H_2ids)(bipy)_2]\cdot 0.5fum\cdot 5H_2O$, where fum = fumaric acid. The H_2ids^{2-} anion retains its betaine structure with monodentate coordination to the Cu atom and has a system of IAHB similar to that of the neutral molecule (see Table 2). One H atom completes two five-membered rings and the other is included in two six-membered rings, the strength of the O...H bonds within each pair of rings being different.

b) Complexones of the nitrilotriacetic acid (H_3nta) class

The single ammonium (betaine) H atom on the N atom in complexones of the H_3nta class is highly active in forming hydrogen bonds, joining up at least two and sometimes three functional groups. Moreover, it participates in the formation of an H-bond with a heteroatom X if the latter is present in the molecule. In complexones of this class it is also possible for four different sets of H-rings to occur:



(V) (VI) (VII) (VIII)

Scheme (V) depicts the structure of $Hnta^{2-}$, H_2nta^-, H_3npda, Hdeg, β-H_2heida, β-H_2heidp, and Hndpma; scheme (VI) depicts the structure of $H_3meata.H_2O$; scheme (VII) shows the structure of H_2mida, $H_4phmida$, H_4cidph; and the structure of H_3nta, H_3ndpa, H_3ntp, and H_5gdph is shown in scheme (VIII).

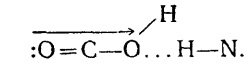
The largest number of examples is included in the first group, where the trifurcated intramolecular N−H...O bond uses the oxygen atoms of all three functional groups as acceptors. Complexones which are characterised by the type of bonding in (VI), where one of the N−H...O bonds is replaced by an N−H...S, have a similar structure (concerning the similarity of the structure of this complexone and the diamino H_4cdta, see below). This type of structure can be called "closed".

Considerably different are the bonding variants (VII) and (VIII), in which one of the functional branches has a transoid rather than the usual twisted conformation relative to the N−H bond, which leads to the disappearance of one of the IAHB ("semi-closed" structure).

In complexones with a closed structure are to be found combinations of acetate groups and propionate, β-hydroxyethyl, and β-propionamide groups, or propionate groups combined with β-hydroxyethyl groups (in β-H_2heidp). It is true that H_3nta itself has a semi-closed structure (one of the two protonated acetate groups does not form an H-ring). However, the anionic forms of this acid (not only nta^{3-} and $Hnta^{2-}$ but also H_2nta^-) have a closed structure. The same applies to H_2nta^- in $Ag(H_2nta)$ and $Hnta^{2-}$ in $Ca(Hnta)\cdot 2H_2O$ and $Na[NaHnta]$.

The β-H_2heida molecule has one interesting feature. Instead of the usual 1c' glycine H-ring it contains an unusual 1c'' isoglycine ring with a set of three H-rings (1$\bar{c}$-1c''-1h) being formed. It would seem that the reason for the inversion of the −COOH group might be the participation of the carboxyl O atom in an energetically more favourable intermolecular O...H−O or O...H−N interaction. However, despite the favourable configuration of the C=O group for this type of interaction, the carboxyl oxygen atom remains completely inert in relation to formation of IEHB of the type O...H−O or O...H−N but, on the other hand, participates in relatively weak IEHB of the type O...H−C.

It is known that IEHB of the type O...H−C is typical of amino acids, peptides, and other bioorganic compounds in which the N atom has an activating effect on the H atom of the neighbouring CH-, CH_2- or CH_3-group.[40] In the case of β-H_2heida the transition to a C−H...O bond, moreover, is encouraged by the weakening of the nucleophilic properties of the carbonyl O atom as a result of the withdrawal of electron density from it along the chain



A complexone which stands somewhat apart from amongst closed complexones of the H_3nta class is β-H_2heidp, in which a set of three H-rings (1$\bar{c}_2$-1c'_2-1h) is formed from two propionate groups and one hydroxyethyl group. The presence of two six-membered H-rings results in a significant weakening of the H-bond in the 1h ring containing the hydroxyethyl group compared to the analogous H-bonds in Hdeg and β-H_2heida, where this H-ring is combined with two five-membered rings.

The remaining complexes of the H_3nta class that were studied have a semi-closed structure. This applies not only to H_3nta itself but also to its analogue H_3ntp. Replacement of the acetate groups in H_3nta by propionate groups does not in principle change anything. Only instead of a combination of two five-membered H-rings (1$\bar{c}$-1c') there is a combination of two analogous six-membered rings (1$\bar{c}_2$-1c'_2) (Fig. 2*a*). It is true that the conformation of the third functional group (−CH_2COOH and −CH_2CH_2COOH respectively), which does not participate in IAHB, is considerably different in the structures of the two acids; the H−N−C−C torsion angles in them are 174 and 48° respectively. But although in this first "bend" because of the small size of the torsion angle this branch in H_3ntp is capable of forming an H-ring, its second "bend", having a planar *trans* structure, turns the O atoms away from the betaine proton. The conformation of the group not participating in the formation of an H-bond is apparently determined by the packing requirements of the crystalline structure as a whole.

A similar structure occurs for nitrilodipropionic acetic acid (H_3ndpa) (Fig. 2*b*), but not for nitrilopropionic diacetic acid (H_3npda). In the latter all three H-rings are formed (Fig. 2*c*). While the semi-closed structure of H_3nta is considered to be an unusual coincidence, it may be assumed that the bifurcate nature of H-bonding in H_3ndpa and H_3ntp arises from the difficulty of forming at the same time two (even more so three) six-membered alanine H-rings because of the steric hindrance that occurs (the weakening of the H-bond involving the hydroxyethyl group in β-Heidp, as mentioned above, is an indication of this).

On the whole the observed variety of combinations of H-rings in the crystals of acids of the H_3nta class with a similar composition, and in particular in the series H_3nta-H_3ntp, is an indication of the strong dependence of the molecular conformation on apparently insignificant changes in the nature of the functional groups in the complexone. However, the possibility cannot be excluded that in solution there are different conformers, whose molecules contain a different number of H-rings. Nevertheless, it should be emphasised that in all of the complexones of this class, regardless of the nature of IAHB (bi- or tri-furcated), uniform sets of H-rings are formed. There is no doubt that the effect of intermolecular interactions is exhibited here to a very much smaller degree than in

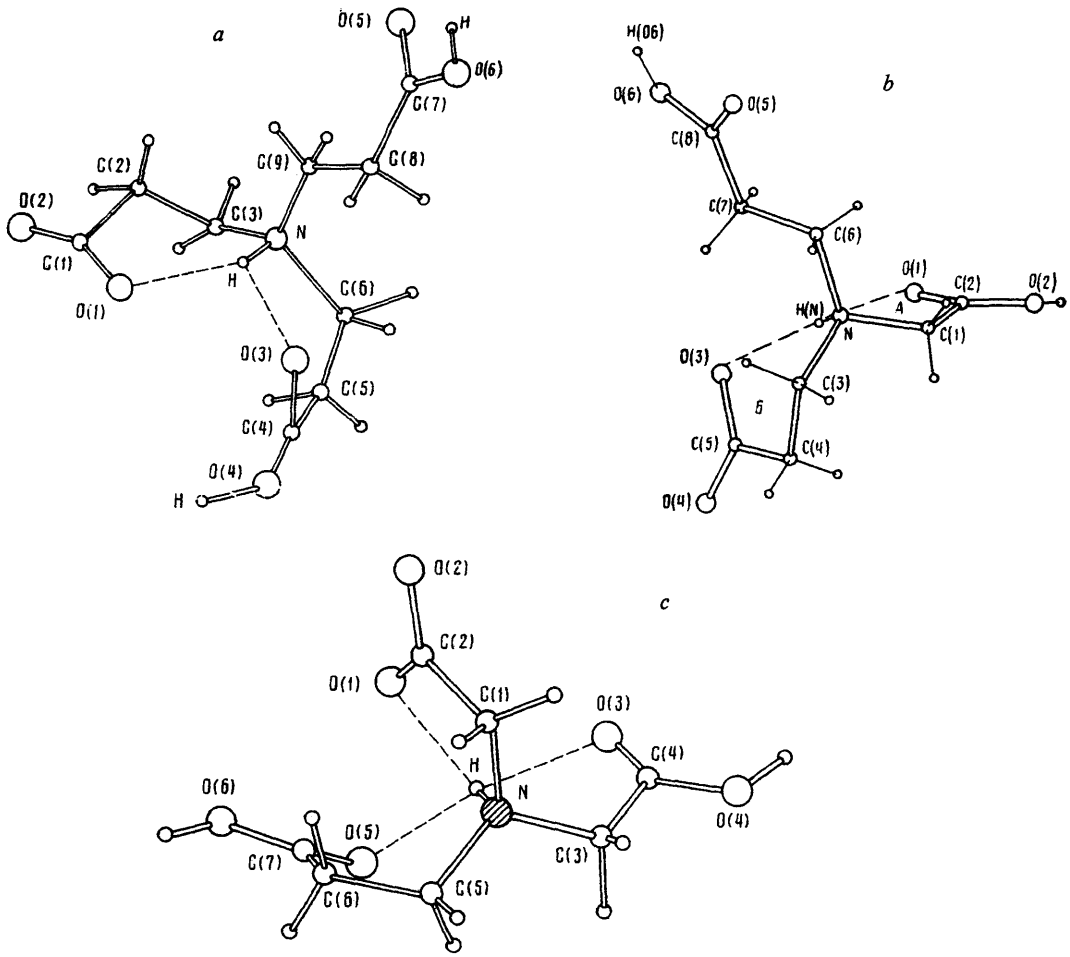


Figure 2. Structure of nitrilotripropionic acid (H_3ntp) (*a*), nitrilodipropionic acetic acid (H_3ndpa) (*b*), and nitrilopropionic diacetic acid (H_3npda) molecules (*c*).

monoaminocarboxylic complexones of the H_2ida class or in aminophosphonic complexones of both classes.

The structural data on "closed" and "semi-closed" compounds of the H_3nta class is sufficiently extensive to permit comparison between the geometric characteristics of H-rings of different types.

In rings of the type $1\bar{c}$ the H...O distances are 2.13–2.27 Å and the angles at the H atoms are 100–116°, while in rings of the type $1c'$ these values are 2.26–2.46 Å and 97–111° respectively. These results indicate a weakening of IAHB on going from glycinate to glycine H-rings. The change from compounds with a "semi-closed" structure to a "closed" structure on deprotonation of H_3nta to H_2nta^- and $Hnta^{2-}$, for example, may be confirmation of this.

There are considerably less structural data on $1h$ and particularly $1c''$ rings. In the $1h$ rings present in Hdeg and β-H_2heida, the H...O distances are in the range 2.21–2.31 Å and the angles at the H atom are 111–116°. In the structure of β-H_2heidp, as was indicated above, there is a pronounced weakening of the H...O bond forming the $1h$ ring (H...O distance 2.61 Å), namely, replacement of acetate groups by propionate groups causes this distance to increase by ~0.4 Å. Further replacement of a hydroxyethyl group by a propionate group in H_3ntp leads to complete ring-opening of one of the H-rings. These changes constitute a clear display of the mutual effect of the H-rings and are probably caused by steric factors.

$1c''$ H-rings were only detected in β-H_2heida and H_4phmida; the H...O distances in them are equal to 2.40 and 2.44 Å and the angles at the H atoms are 101 and 100°. Because of the lack of data, it may be concluded only provisionally that the $1c''$ isoglycine rings have the lowest strength while the $1\bar{c}'$ glycine and $1h$ nitrilohydroxyethyl rings have approximately the same strength but lower than for $1\bar{c}$ glycinate rings.

The intermediate position of the $1h$ ring is supported by a comparison of the geometry of IAHB in Hdeg and β-H_2heida. In the first of these the H-bond involving the $1\bar{c}$ glycinate group is considerably stronger than that involving the $1h$ hydroxyethyl group, in the second the H-bond involving the hydroxyethyl group is stronger than that involving the $1c''$ isoglycine group. The H...O distances in $1\bar{c}_2$ alanine rings are almost constant (~2.11 Å) and are virtually no different from the lower limit of the distances in $1\bar{c}$ rings. On the other hand, in $1c'_2$ alanine rings, as in $1c'$ rings, the

H...O distances vary over a wide range and are also considerably longer than those in $1\bar{c}$ rings (2.31–2.50 Å).

The transition from five-membered to six-membered rings gives rise to considerably greater changes in the angles at the H atoms. They increase substantially (by more than 20°)—123–137° in the case of $1\bar{c}_2$ and 117–127° for $1c'_2$.

IAHB is least strong in aminophosphonic complexones. This applies primarily to the phosphonate or phosphonic groups themselves. In many cases they do not participate at all in the formation of H-rings (such as H_4phmida, H_6ntph, H_5gdph, H_4eadph, H_3phmg, and in the structure of H_3phmg·½HCl). Sometimes the formation of H-rings can only be hypothetically assumed, since the H...O distances in them increase to 2.48–2.92 Å. The other types of H-rings in these compounds also prove to be weakened, in particular for $1c'$ (in H_3phmg, H_4phmida, H_5gdph the H...O distances are 2.38–2.59 Å and the angles at the H atom are 90–106°), while a $1h_2$ ring is not formed at all in H_3phma (only intermolecular H-bonds occur in the structure). It would appear that in the case of monoaminophosphonic complexones it is only possible to indicate that there is a tendency to form H-rings, which occurs only when the molecular packing conditions are favourable.

These same groups, $-CH_2PO_3H^-$ and $CH_2PO_3H_2$, are possibly dependent on a purely conformational factor. Non-bonded interactions between the substituents in the two tetrahedral groups—phosphonic and methylene—make the most eclipsed conformation necessary for the approach of one of the atoms of the phosphonate group to the ammonium atom less favourable.

The groups described may be arranged in the following series of decreasing H-acceptor activity:

$$COO^- > COOH_{=O} > CH_2CH_2OH > COOH_{OH} > PO_3H^-,\ PO_3H_2$$

IV. Structure of diamino and triamino complexones

The list of structurally investigated diamino complexones known to the present authors includes eight diaminocarboxylic acids, four of their cationic and three of their anionic forms, three diaminophosphonic complexones and the cationic form of one of these (Table 1). The structure of a single triaminocarboxylic complexone is also known.

By analogy with monoamino complexones, diamino complexones can also be divided into two classes: those with ammonium centres each containing two hydrogen atoms [the ethylenediamine-*N*,*N'*-diacetic acid (H_2edda) class] and those with ammonium centres each containing one betaine hydrogen atom [the ethylenediamine-*N*,*N*,*N'*,*N'*-tetraacetic acid (H_4edta) class].

Depending on the nature of the intramolecular H-rings formed, diamino complexones of both classes can be subdivided into three groups—open, semi-open, and closed. Compounds that do not form IAHB belong to the first group. In fact, this type of structure only occurs for the cationic forms of two complexones with propionate substituents—H_4eddp^{2+} and H_6edtp^{2+} as their hydrochlorides.

The second group includes compounds whose IAHB only join atoms that belong to their "own" half of the diamino complexone. H-rings characteristic of monoamino complexones are formed, and also as a rule in similar combinations, so such complexones can be called "quasi-monoamino".

The third group is made up by complexones that contain "crossed" IAHB between the atoms of the different halves of the molecule in addition to the IAHB of each monoamino moiety.

It is not difficult to realise that the formation of closed diamino complexones requires a twisted structure of the central (usually ethylenediamino) section. Complexones with a semi-open and open structure always have an unfolded transoid structure of the central section, which may be both the cause and the effect of the quasi-monoamino nature of their system of IAHB. The H_4eddp^{2+} cation, which has an open structure, and the H_2eddp molecule with a semi-open structure, are shown in Fig. 3*a* and 3*b* as examples.

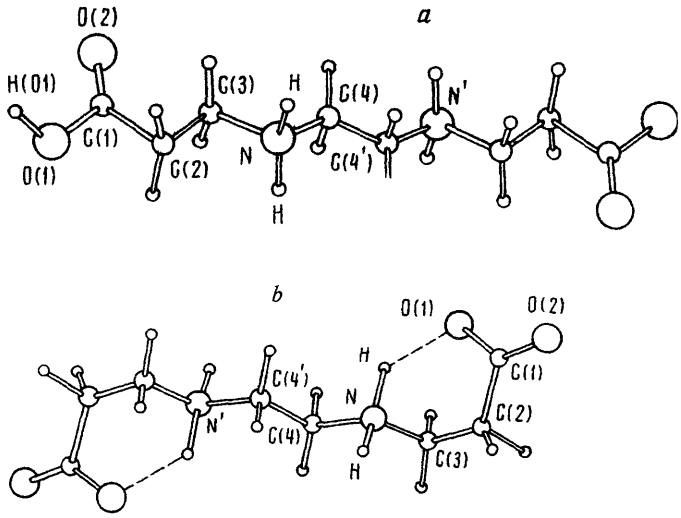


Figure 3. Structure of the H_4eddp^{2+} cation (*a*) and ethylenediamine-*N*,*N'*-dipropionic acid (H_2eddp) molecule (*b*).

In Table 3 all of the diamino complexones (and the triamino H_5dtpa) of both classes are assigned to their respective groups. It follows from Table 3 that almost all of the complexones from the H_2edda class have an open or semi-open structure. The presence of two H atoms on each ammonium centre is likely to lead to the degree of weakening of IAHB of the type N–H...O at which the strained folded structure becomes unstable. The only exception is $H_4edds \cdot 5H_2O$, which is probably related to the specific nature of the succinate groups.

Amongst those compounds that belong to the H_4edta class, all three structural variants have been found—open (in the H_6edtp^{2+} cation), semi-open (in five neutral molecules, two anions, and one cation), and closed (in five neutral molecules, one anion, and one cation).

As expected, a semi-open structure occurs in complexones with an elongated or complex hydrocarbon chain in the central section, as in H_4dbata, H_4dbeta, H_4dhobta, H_2oadp, and H_4egta (see Table 1 for structural formula), which hinders the formation of crossed hydrogen bonds. The molecules of H_2oadp§ and H_4dhobta are

§ The structure of the H_2oadp complexone is unique. This complexone is intermediate between semi-open and closed types. Its central section contains two carbonyl O atoms, so that it can form two intersecting five-membered H-rings without changing to a twisted conformation. Similar rings are also retained in the $oadp^{2-}$ anion, which is coordinated on two sides with Cu atoms in $[Cu(oadp)(bipy)(H_2O)_2] \cdot H_2O$ (Fig. 4*b*).

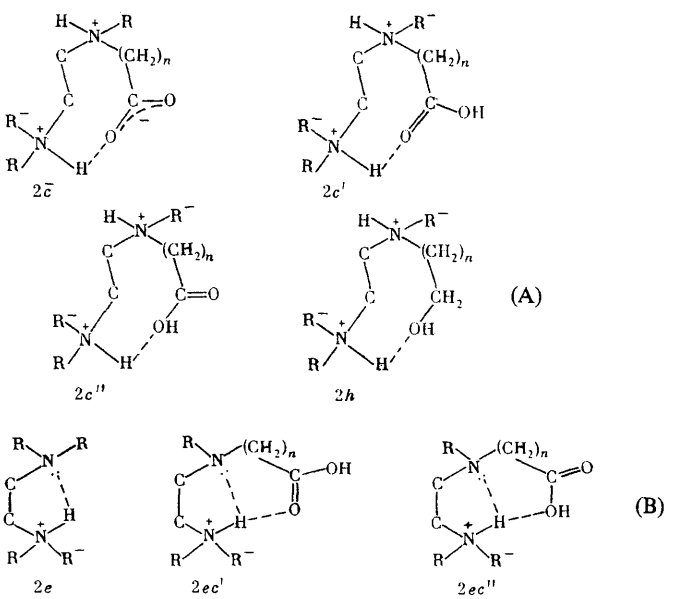
Table 3. Division of structurally investigated diamino and triamino complexones and their cationic and anionic forms into classes (H_2edda and H_4edta) and groups (different types of structure).

Group	H_2 edda class	H_4 edta class
Open structure	$[H_4eddp]^{2+}$ в $[H_2eddp]\cdot 2HCl$	$[H_6edtp]^{2+}$ в $[H_4edtp]\cdot 2HCl$
Semi-open structure (unfolded conformation of the central section)	$H_2eddp\cdot 2H_2O$ $H_4eddph\cdot 2H_2O$ $H_4eddiph\cdot 2H_2O$ $[H_6eddiph]^{2+}$ в $[H_4eddiph]\cdot 2HCl\cdot 2H_2O$ H_2oadp $oadp^{2-}$ в $[Cu(oadp)bipy(H_2O)_2]\cdot H_2O$	$[H_6edta]^{2+}$ в $[H_4edta]\cdot 2HCl\cdot 3H_2O$ $[H_2edta]^{2-}$ в $[Mg(H_2O)_6](H_2edta)$ $[H_2edta]^{2-}$ в $[Rb_2(H_2edta)]\cdot 2H_2O$ $H_4dbata\cdot 2H_2O$ $H_4dbeta\cdot 2H_2O$ $H_4dhobta\cdot 2H_2O$ $[H_5edta]^{+}$ в $[H_4edta]HBr\cdot H_2O$
Closed structure (twisted conformation of the central section)	$H_4edds\cdot 5H_2O$	H_4edta $[H_2edta]^{2-}$ в $K_2(H_2edta)\cdot 2H_2O$ $H_4cdta\cdot H_2O$ $[H_6cdta]^{2+}$ в $[H_6cdta][PdCl_4]$ H_5dtpa $H_8edtph\cdot H_2O$

depicted in Fig. 4*a* and 4*c* as examples. More curious and less easy to understand is the fact that anionic forms of the reference complexes H_2edta^{2-} in two compounds (Rb and Mg salts), in the same way as the cationic form H_5edta^{+} in hydrobromide, have an unfolded structure, while the same H_2edta^{2-} anion in the potassium salt and the acid itself (H_4edta) have a twisted conformation. This disparity evidently indicates that both forms are approximately equivalent in terms of energy and they are selected according to the specific composition of the compound as a whole. In particular, the change to a strongly acid medium, which creates the conditions for the formation of H_5edta^{+} from H_4edta, results in cleavage of the crossed N—H...O bonds, and hence leads to the conformation of the central section changing from twisted to transoid (Fig. 5*a* and 5*b*).

Finally, it is worth noting that neither the absence nor the presence of crossed IAHB are necessarily an indication of "symmetry" of the composition and conformation of the substituents of the two halves of the molecule. Symmetry in protonation of the carboxylate groups is absent, in particular in the semi-open H_4dhobta (Fig. 4*b*) and in the protonation of N atoms in H_4cdta (but not H_6cdta^{2+}) and H_5dtpa (Figs. 6 and 7). Finally, in the phosphonic complexone H_8edtph (Fig. 8), while there is complete "symmetry" of composition (see Table 3), symmetry is absent in the formation of IAHB. The structural features of these complexones will be examined below in greater detail.

In the molecules and ions with a semi-open structure, only those H-rings which are characteristic of monoamino complexones are possible. In complexones of a closed structure with crossed H-bonds, additional H-rings are formed, containing two nitrogen atoms:



The first group (A) comprises eight-membered rings (when $n = 1$) with N—H...O bonds; these are $2\bar{c}$, $2c'$, and $2c''$ H-rings based on a carboxylate substituent and a $2h$ H-ring based on a hydroxyethyl

substituent.¶ The second group (B) is made up by five-membered H-rings (when $n = 1$) with N—H...N bonds that occur when one of the two nitrogen atoms is quaternised; these are 2*e* (in a pure form), 2*ec'* and 2*ec''* (with additional expansion to eight-membered cyclic analogues of 2*c'* and 2*c''* rings). Such rings occur in the diamino H_4cdta and the triamino H_5dtpa (see structural formulae in Table 1 and Figs. 6 and 7). We should point out that the five-membered 2*e* ring may be regarded as an analogue of a 1*t* ring and hence a diamino complexone may formally be regarded as a monoamino complexone (and triamino like diamino) with an N heteroatom (carrying an unshared electron pair) as one of the substituents.

Let us pause to consider asymmetric complexones in somewhat greater detail. It is clear from Fig. 4*c* that the asymmetry of H_4dhobta arises not only because both carboxyl groups bound to one N atom are deprotonated while both of those bound to the other N* nitrogen atom are protonated. The difference also occurs because the H(N) atom takes part in the formation of a trifurcated bond with the two ionised atoms O(1) and O(3) and with the O(5) atom of the hydroxyl group in the neutral residue, while the H(N)* only participates in a bifurcated bond with the carbonyl atoms O(1)* and O(3)*. This results from the specific manner of unfolding of the successive units of the chain in the central section, leading to a convergence of the O(5) and H(N) atoms but not the O(5)* and H(N)* atoms.

The structure of the H_4cdta molecule, in which only one N(1) atom is quaternised, is depicted in Fig. 6. Its H(N1) proton participates accordingly in the formation of a trifurcated bond, forming a five-membered 2*e* ethylenediamine (*E*) H-ring and five-membered $1\bar{c}$ glycinate (*A*) and 1*c'* glycine (*B*) rings.

The structure of the triamino complexone H_5dtpa is shown in Fig. 7. Here also not all but only two of the three nitrogen atoms—the central N(1) atom and one of the lateral N(2) atoms—are quaternised, although the lateral nitrogen atoms are known to have a higher basicity than the central atom. In essence, the molecule may be regarded as a diamino complexone with a bis-zwitterion structure [the N(1) and N(2) atoms] and an analogue of H_4edta with replacement of one of the acetate groups by an ethyleneaminoacetate group. The N(2) atom, in the same way as in H_4edta, belongs simultaneously to three conjugated H-rings involving acetate groups (rings *A*, *B*, and *C* in Fig. 7), one of which (*C*) is crossed. Replacement of one of the acetate groups on the N(3) atom by an ethyleneaminoacetate group permits the H(N1) atom to form only two rings—an ethyleneamino ring (*E*), the same as in H_4cdta, and an eight-membered ring involving an acetate group (*D*), namely the combination labelled above as 2*ec'*. The geometric properties of the N—H...N bond in H_5dtpa and H_4cdta are very similar (Table 4). Thus, both the molecular geometry and the system of IAHB in H_5dtpa combine typical features of H_4edta and H_4cdta. The triaminocarboxylic complexone is made up of standard sets of H-rings that are typical of monoamino- and diamino-carboxylic complexones.

Perhaps the most individual structure is that of the methylphosphonic diamino complexone H_8edtph (Fig. 8) (for structural formula, see Table 1).

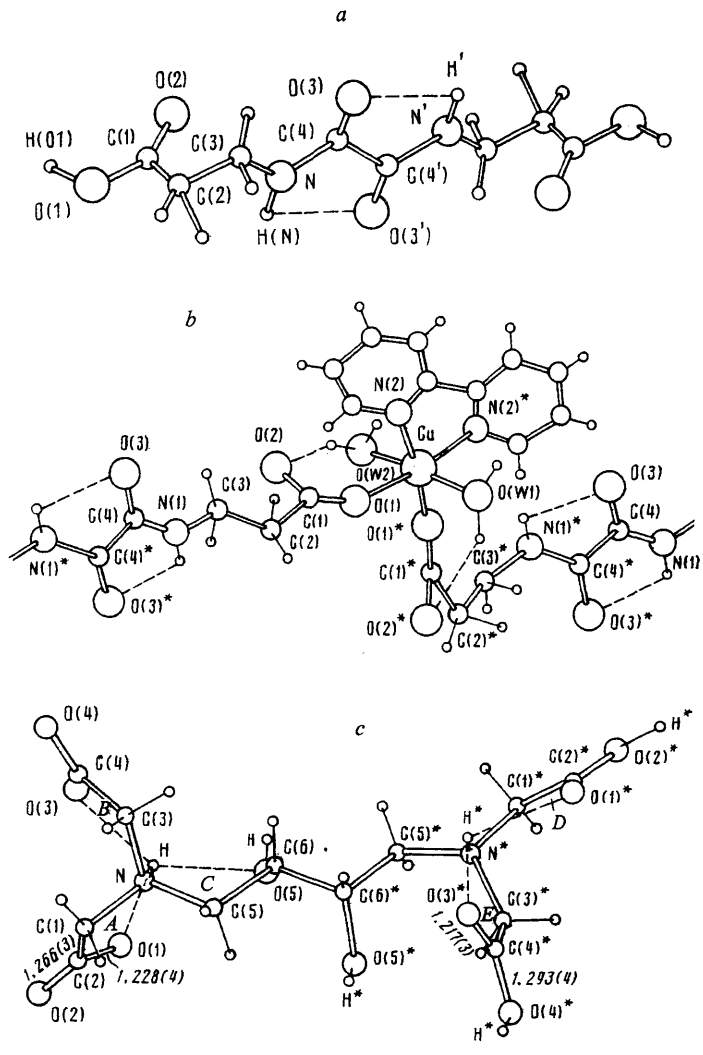


Figure 4. Structure of the oxamido-*N*,*N'*-dipropionic acid (H_2oadp) molecule (*a*), a section of the polymeric chain structure of $[Cu(oadp)(bipy)H_2O)_2]\cdot H_2O$ containing $oadp^{2-}$ anions (*b*), and the 2,3-hydroxy-1,4-butanediamine-*N*,*N*,*N'*,*N'*-tetraacetic acid molecule (*c*). Primes are used to denote atoms that are related by symmetry elements and asterisks are used to denote crystallographically independent atoms in the second half of the molecule.

At first glance it resembles the structure of the H_4edta molecule. It has the same twisted conformation of the central ethylenediamino residue (with a dihedral angle of 86° instead of 67°), there are H-rings that include only their "own" phosphonate and also "crossed" rings that involve a "foreign" phosphonate group. In fact, however, there is only one nitrilomethylphosphonate H-ring ($1\overline{ph}$) (ring *A* in Fig. 8); the remaining three six-membered rings—$1\overline{ph}''_{C-H}$ and $1ph'_{C-H}$ (crossed) and $1ph''_{C-H}$ (terminal) (*B*, *C*, and *D*)—are formed by C—H...O bonds rather than N—H...O.

¶ Variants based on phosphonate or phosphonic groups have not been given since molecules with such types of H-ring have so far not been detected.

The specific nature of methylphosphonic complexones is manifested in this (as mentioned above in connection with similar IAHB in monoamino complexones). It is natural that the hydrogen bonds in these H-rings are some of the weakest.

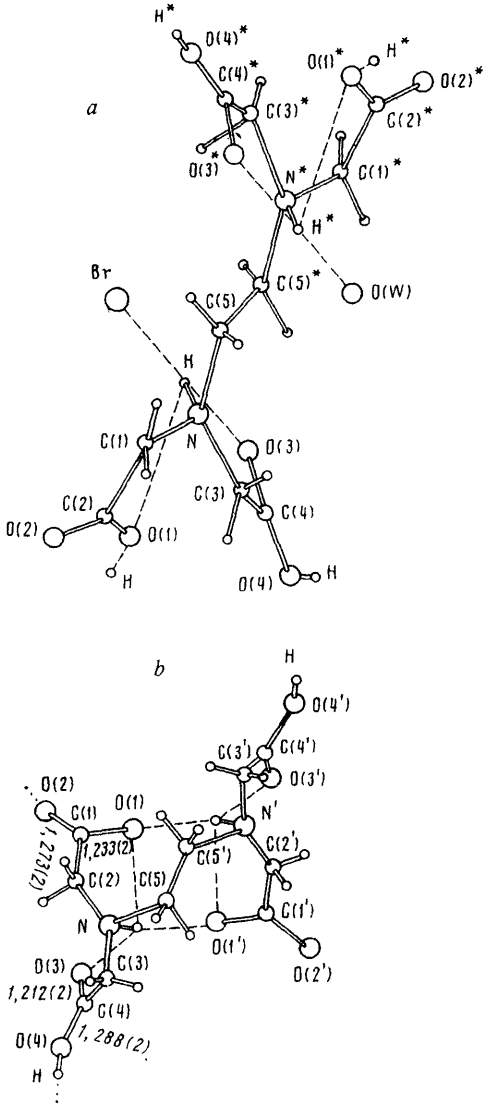
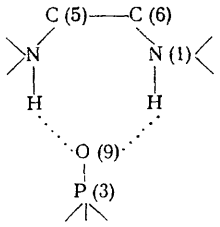


Figure 5. Structure of the H_5edta^+ cation (*a*) and ethylenediamine-*N*,*N*,*N'*,*N'*-tetraacetic acid (H_4edta) molecule (*b*).

N^+-H groups of the central section of the molecule



so that a seven-membered H,H-ring is formed.

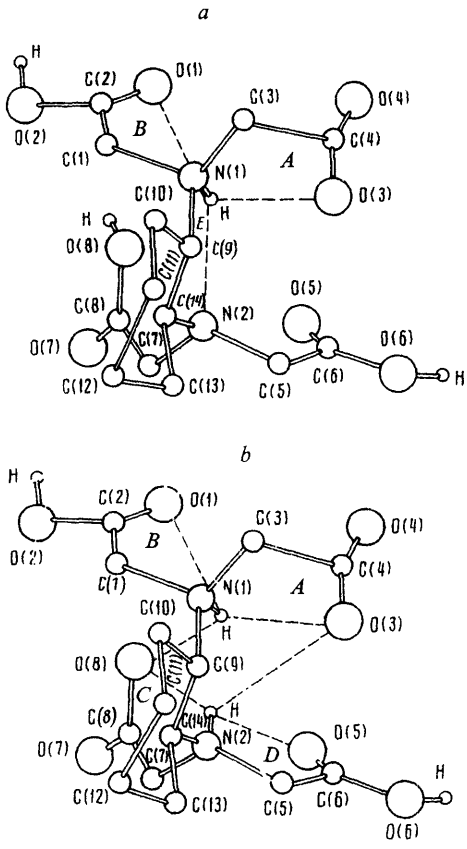


Figure 6. Structure of the *trans*-1,2-cyclohexanediamine-*N*,*N*,*N'*,*N'*-tetraacetic acid molecule (*a*) and its hypothetical tautomeric form (*b*).

In H_8edtph there is perhaps the clearest exhibition of the tendency of methylphosphonate complexones to form intermolecular N–H...O hydrogen bonds involving the oxygen of a phosphonic or phosphonate group rather than intramolecular hydrogen bonds. An unusual feature of the crystalline structure of this compound is also that the O(9) atom of the phosphonate group of the neighbouring complexone forms an IEHB simultaneously with two

In the majority of the asymmetric complexones described there are short intermolecular hydrogen bonds of the type O...H...O, where the potential lability of the proton makes the description of the sets of H-rings in them not completely unequivocal (it opens up the possibility of a $1\bar{c}$ ring involving a COO^- group being replaced by a $1c'$ or $1c''$ ring involving a COOH group and vice versa). This question is considered in greater detail in the next section.

The geometric properties of hydrogen bonding (IAHB and IEHB) in the diamino and triamino complexones studied are given in Table 4. The labelling of the "sets"—the combinations of conjugated H-rings—is also given here.

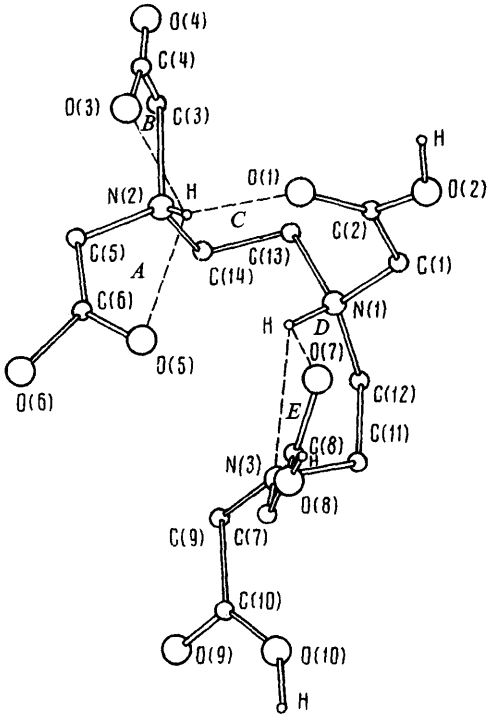


Figure 7. Structure of the diethylenetriamine-*N*,*N*,*N'*,*N''*,*N''*-pentaacetic acid (H_5dtpa) molecule.

Comparison of the H...O distances and angles at the H atoms in diamino complexes is perhaps not so indicative as in monoamino complexones, mainly because of the intervention of intermolecular O...H...O bonds that increase the lability of the hydrogen atoms. If the clear examples of this type of interference are set aside (indicated by additional symbols in brackets in the labelling of the H-rings in Table 4), all of the H...O distances in rings of the type $1\bar{c}$ or $2\bar{c}$ fall within the region of 2.00–2.38 Å and the angles at the H atom are 101–132° while in rings of the type 1*c'* the distances are in the range 2.17–2.52 Å and the angles are 94–124°. In the only "pure" 1*c''* ring the O...H distance and N–H...O angle are equal to 2.42 Å and 95° respectively, while in the only 1*h* ring these values are 2.41 Å and 106°. At any rate these results are not at variance with the series of H-acceptor activity which was put forward on the basis of the structures of monoamino complexones.

Bonds of the type C–H...O (H...O equal to 2.27, 2.35 and 2.37 Å) which are found in the diamino complexone H_8edtph are somewhat shorter than the analogous bonds in monamino acids, while the angles at the H atom are greater than 140°.

V. Prototropic tautomerism in aminocarboxylic complexones

In the crystal structures of some of the mono- and diaminocarboxylic complexones discussed and also in the triamino complexone H_5dtpa short intramolecular hydrogen bonds of the type O...H...O occur (usually slightly asymmetric) with an O...O distance in the range 2.43–2.49 Å and an angle at the H atom in the range 160–180°. In certain cases studies have revealed two possible positions of the hydrogen atom between the oxygens. Short H-bonds can combine acidic groups of neighbouring molecules into dimer pairs or chains.

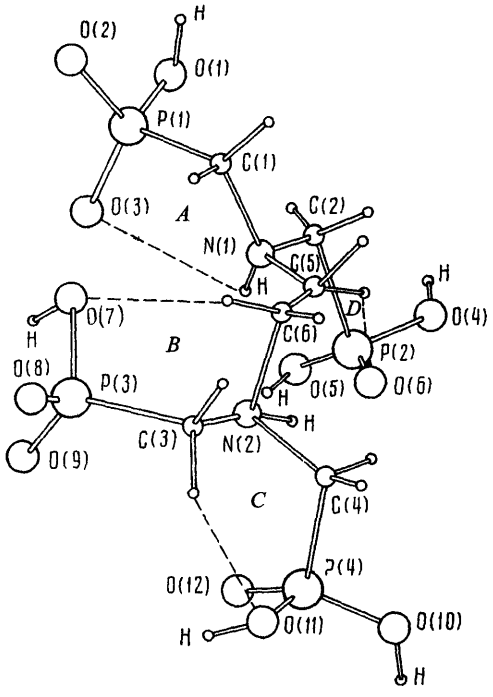
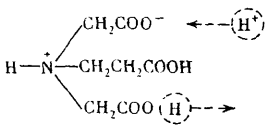


Figure 8. Structure of the ethylenediamine-*N*,*N*,*N'*,*N'*-tetramethylphosphonic acid (H_8edtph) molecule.

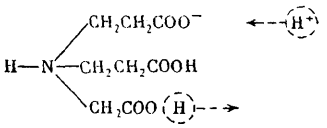
This fact suggests the possibility of tautomeric rearrangement in solution by migration of a proton or, at least, the possibility of two tautomeric forms existing in a given proportion. This suggestion is based on the somewhat unusual distribution of hydrogen atoms amongst the acid groups and on the unexpected asymmetry of some complexones.

In crystals of nitrilopropionic diacetic acid (H_3npda) one of the acetate groups is deprotonated. At the same time there is a "short" O–H...O bond of length 2.460(4) Å between the CH_2COOH groups of one molecule and CH_2COO^- groups of another [see scheme (IX) and Fig. 2*c*]. The tautomeric rearrangement on migration of a proton does not give rise to any fundamental change in the chemical structure of the molecule—deprotonated and protonated acetate groups are preserved. It is different with the

structure of nitrilodipropionic acetic acid (H_3ndpa) [see scheme (X) and Fig. 2*b*]:

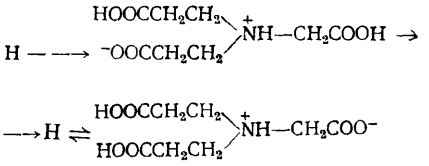


(IX)



(X)

It is somewhat surprising that in the presence of the more acidic acetate group it is one of the propionate groups that is actually deprotonated. However, the short hydrogen bond of length 2.467(8) Å between the hydrogen atom of a CH_2COOH group and the oxygen atom of a $CH_2CH_2COO^-$ group suggests the possibility of a tautomeric rearrangement occurring when the molecule passes into solution to form a more stable zwitterion form:



In the structure of the semi-open diamino complex H_4dhobta (see Fig. 4*c*) the asymmetry in the arrangement of CH_2COO^- and CH_2COOH groups (two CH_2COO^- groups are situated on the N atom and two CH_2COOH groups are on the N* atom) is unexpected. However, there is a short intermolecular hydrogen bond O(4)*—H(O4)*...O(2) between the O(4)* and O(2) atoms of neighbouring molecules. The O(4)*...O(2) distance is equal to

Table 4. Geometric properties of N—H...O and N—H...N hydrogen bonds in the structures of diaminocarboxylic, triaminocarboxylic, and diaminophosphonic complexones, anions, and cations.

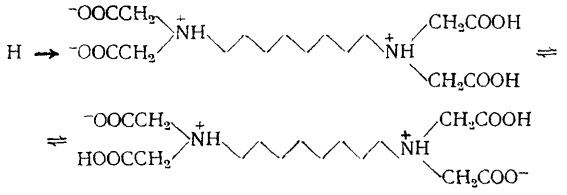
Complexone, anion or cation	Labelling of H-ring or IEHB	Geometry of N—H...O(N) bond				Sets of H-bonds
		Distance, Å			N—H...O (N—H...N) angle, deg	
		N—H	H...O (H...N)	N...O (N...N)		
H_2eddp·$2H_2O$	$1\bar{c}_2$	0.95(3)	2.56(4)	3.119(5)	118(2)	$1\bar{c}_2$-IEHB
	IEHB	0.95(3)	1.87(4)	2.774(5)	157(2)	
	IEHB	1.07(3)	1.61(4)	2.662(5)	165(2)	IEHB
H_2oadp	1*c*′	0.85(4)	2.30(4)	2.711(4)	110(3)	1*c*′-IEHB
	IEHB	0.85(4)	2.21(4)	3.010(4)	156(3)	
$oadp^{2-}$ in $[Cu(oadp)(bipy)(H_2O)_2]H_2O$ (Ref.19)	1*c*′	0.86(3)	2.30(3)	2.683(3)	107(4)	1*c*′-IEHB
	IEHB	0.86(3)	2.19(3)	2.918(3)	143(4)	
	1*c*′	0.76(3)	2.50(3)	2.781(3)	104(3)	1*c*′-IEHB
	IEHB	0.76(3)	2.15(3)	2.861(3)	157(3)	
H_4dbata·$2H_2O$	$1\bar{c}$(1*c*″)	0.90(2)	2.46(3)	2.687(3)	95(2)	$1\bar{c}$-1*c*′-IEHB (1*c*″-1*c*-IEHB)
	1*c*′($1\bar{c}$)	0.90(2)	2.24(3)	2.714(3)	113(2)	
	IEHB	0.90(2)	2.18(2)	2.877(3)	134(2)	
H_4dbeta·$2H_2O$	$1\bar{c}$(1*c*″)	0.87(3)	2.53(3)	2.707(3)	92(2)	$1\bar{c}$-1*c*′-IEHB (1*c*″$1\bar{c}$-IEHB)
	1*c*′($1\bar{c}$)	0.87(3)	2.22(3)	2.703(2)	115(2)	
	IEHB	0.87(3)	2.14(3)	2.838(2)	137(3)	
H_4dhobta·$2H_2O$	$1\bar{c}$	0.91(3)	2.23(2)	2.672(3)	106(2)	$1\bar{c}$-$1\bar{c}$-1*h* ($1\bar{c}$-1*c*′-1*h*)
	$1\bar{c}$(1*c*′)	0.91(3)	2.03(2)	2.628(3)	122(2)	
	1*h*	0.91(3)	2.41(2)	2.804(3)	106(2)	
	1*c*′	0.98(3)	2.33(3)	2.723(3)	103(2)	1*c*′-1*c*′-IEHB ($1\bar{c}$-1*c*′-IEHB)
	1*c*′($1\bar{c}$)	0.98(3)	2.11(3)	2.652(3)	113(2)	
	IEHB	0.98(3)	2.24(3)	3.011(3)	135(2)	
H_4egta	1*c*′	0.89(3)	2.27(2)	2.217(3)	111(2)	1*c*′-1*c*′-IEHB
	1*c*′	0.89(3)	2.45(2)	2.746(2)	100(1)	
	IEHB	0.89(3)	2.11(2)	2.862(2)	142(2)	
H_4edta	$1\bar{c}$(1*c*′)		2.33(3)	2.748(2)	108	$1\bar{c}$-1*c*′-$2\bar{c}$ ($1\bar{c}$-1*c*′-2*c*′)
	2*c*(2*c*′)		1.95(3)	2.787(2)	152	
	1*c*′($1\bar{c}$)		2.39(3)	2.682(2)	99	

Table 4 (cont'd).

Complexone, anion or cation	Labelling of H-ring or IEHB	Geometry of N–H...O(N) bond				Sets of H-bonds
		Distance, Å			N–H...O (N–H...N) angle, deg	
		N–H	H...O (H...N)	N...O (N...N)		
H_2edta^{2-} in $[K_2H_2edta)].2H_2O$ (Ref.41)	$1\bar{c}$			2.610		$1\bar{c}$-$1\bar{c}$-$2\bar{c}$
	$1\bar{c}$			2.512		
	$2\bar{c}$			2.928		
	$1\bar{c}$			2.736		$1\bar{c}$-$1\bar{c}$-$2\bar{c}$
	$1\bar{c}$			2.809		
	$2\bar{c}$			2.714		
H_2edta^{2-} in $[Mg(H_2O)_6](H_2edta)$ (Ref.42)	$1\bar{c}$	0.89	2.38(2)	2.708(2)	102	$1\bar{c}$-$1\bar{c}$-IEHB
	$1\bar{c}$	0.89	2.18(2)	2.660(2)	113	
	IEHB	0.89	2.22(2)	2.899(2)	132	
H_2edta^{2-} in $Rb_2(H_2edta).2H_2O$ (Ref.43)	$1\bar{c}$			2.61		$1\bar{c}$-$1\bar{c}$-IEHB
	$1\bar{c}$			2.63		
	IEHB			2.63		
	$1\bar{c}$			2.60		$1\bar{c}$-$1\bar{c}$-IEHB
	$1\bar{c}$			2.74		
	IEHB			2.96		
H_5edta in $[H_5edta]Br.H_2O$ (Ref.39)	$1\bar{c}(1c'')$	0.90(7)	2.40(6)	2.646(5)	96(5)	$1\bar{c}(1c')$-$1c'$-IEHB
	$1c'$	0.90(7)	2.18(6)	2.718(5)	118(6)	
	IEHB(Br)	0.90(7)	2.61(7)	3.282(6)	132(6)	
	$1c''(1\bar{c})$	0.85(7)	2.42(6)	2.651(5)	95(5)	$1c''(1\bar{c})$-$1c'$-IEHB
	$1c'$	0.85(7)	2.17(6)	2.700(6)	120(6)	
	IEHB	0.85(7)	2.18(7)	2.847(7)	134(6)	
H_6edta^{2+} in $[H_6edta]Cl.3H_2O$ (Ref.44)	$1c'$	1.06	2.20	2.69(2)	106(8)	$1c'$-$1c'$-IEHB
	$1c'$	1.06	2.41	2.67(2)	104(8)	
	IEHB(Cl)	1.06	2.35	3.17(1)	133(7)	
	$1c'$	1.10	2.07	2.70(2)	114(8)	$1c'$-$1c'$-IEHB
	$1c'$	1.10	2.48	2.71(2)	90(8)	
	IEHB(Cl)	1.10	2.34	3.15(1)	129(7)	
$H_4edds \cdot 5H_2O$	$1\bar{c}$		2.20	2.668	107	$1\bar{c}$-$1c'_2$-$2\bar{c}$
	$2\bar{c}$, $1c'_2$		2.20	2.784, 2.952	132	
$H_4cdta \cdot H_2O$	$1c$	0.99(4)	2.27(4)	2.652(4)	101(2)	$1\bar{c}$-$1c'$-$2e$
	$1c'$	0.99(4)	2.52(4)	2.771(4)	94(2)	
	$2e$	0.99(4)	2.25(4)	2.825(3)	116(3)	
H_6cdta^{2+} in $[H_6cdta][PdCl_4].5H_2O$ (Ref.45)	$1c'$			2.718		$1c'$-$1c'$-$2c'$
	$1c'$			2.662		
	$2c'$			2.858		
	$1c'$			2.723		
	$1c'$			2.693		$1c'$-$1c'$-$2c'$
	$2c'$			2.894		
H_5dtpa	$2e$	0.95(4)	2.23(4)	2.830(3)	120(3)	$2ec'$
	$1c'$	0.95(4)	2.34(4)	2.975(3)	124(3)	
	$1\bar{c}$	0.91(4)	2.21(4)	2.673(3)	111(3)	$1\bar{c}$-$1c'$-$2\bar{c}$ ($1c$-$1\bar{c}$-$2c'$)
	$2\bar{c}(2c')$	0.91(4)	2.24(4)	2.991(4)	140(3)	
	$1c'(1\bar{c})$	0.91(4)	2.46(4)	2.696(3)	95(3)	
$H_4eddph \cdot 2H_2O$	$1\overline{ph}''$	0.83(6)	2.68(5)	2.885(4)	96(5)	$1\overline{ph}''$-IEHB
	IEHB	0.83(6)	1.97(6)	2.733(5)	154(5)	
	IEHB	0.87(5)	1.86(5)	2.693(5)	162(5)	IEHB
$H_4eddiph \cdot 2H_2O$*	$1\overline{ph}'$	1.06(10)	2.27(10)	2.812(17)	110(7)	$1\overline{ph}'$-IEHB
	IEHB	1.06(10)	1.99(11)	2.944(19)	148(8)	
	IEHB	1.27(16)	1.38(16)	2.618(20)	162(9)	IEHB
$H_6eddiph^{2+}$ in $[H_6eddiph]Cl_2.2H_2O$ (Ref.29)	$1\overline{ph}'$	0.97(4)	2.51(4)	2.882(3)	103(2)	$1\overline{ph}'$-IEHB
	IEHB	0.97(4)	1.86(4)	2.801(3)	163(3)	
	IEHB(Cl)	0.87(4)	2.28(4)	3.126(3)	168(3)	IEHB
$H_8edtph \cdot H_2O$	$1\overline{ph}'$	0.79(4)	2.61(4)	2.970(4)	110(3)	$1\overline{ph}'$-IEHB
	IEHB	0.79(4)	1.98(4)	2.733(4)	160(4)	
	IEHB	0.81(3)	1.90(3)	2.689(4)	163(3)	IEHB

*Random distribution of O atoms of phosphonic groups.

2.470(2) Å, the H-bond is almost symmetrical, and the C–O bonds in the groups that are linked are evidently capable of undergoing tautomeric rearrangement by delocalisation of π-interaction. In the O(1)–C(2)–O(2) group they are equal to 1.228(4) and 1.266(3) Å respectively while in the O(3)*–C(4)*–O(4)* group they are 1.217(3) and 1.293(3) Å in length. Under these conditions it is natural to expect a tautomeric change to a symmetrical form on solution:



Short O–H...O IEHB also occur in a number of closed diamino complexones, and primarily in H_4edta itself (Fig. 5*b*). The O(4)...O(2) distance in short IEHB is equal to 2.460(2) Å, and the O(4)–H and O(2)...H distances are 1.20(3) and 1.28(3) Å. It is the acetate groups that are able to undergo rearrangement (see Fig. 5*b*). In the COOH group the π-electrons are not completely localised and in the COO^- group they are delocalised. When tautomeric rearrangement occurs in both halves of the molecule the $1\bar{c}-1c'-2\bar{c}$ sets of H-rings are changed to $1c'-1\bar{c}-2c'$. The molecular symmetry as a whole is not disturbed.

The asymmetric structures of the diamino H_4cdta and triamino H_5dtpa complexones are the most interesting in relation to the present topic. It is not difficult to see (see Fig. 6*a*) that the position of one of the carboxyl groups bonded to the non-protonated N(2) atom [the group containing the O(8) and H(O8) atoms] is such that the molecule as a whole is capable of forming an O(8)...H(N1)–N(1) bond. Although the O(8)–H(N1) distance is quite long (2.62 Å), a small change in the conformation of the central section could lead to cleavage of the N(1)–H(N1)...N(2) bond and formation of an N(1)–H(N1)...O(8) bond with replacement of the $1\bar{c}-1c'-2e$ set by a $1\bar{c}-1c'-2c''$ set. If a subsequent tautomeric transfer of the H(O8) proton from the O(8) atom to N(2) is assumed, the complex would acquire a symmetrical structure similar to that of H_4edta, with $1\bar{c}-1c'-2\bar{c}$ sets (see Fig. 6*b*).

Such a possibility is supported by the completely symmetrical closed structure of the H_6cdta^{2+} cation, in which both nitrogen atoms are quaternised. Since the synthesis of $[H_6cdta]^{2+}[MCl_4]^{2-}$ complexes, where M = Pd and Pt, occurs in hydrochloric acid solutions, we can suggest the nature of the changes in the structure of H_4cdta on going from a less acidic medium to a more acidic one.

The N...N distances in H_4edta, H_6cdta^{2+}, and H_4cdta are equal to 3.195, 3.102, and 2.825 Å respectively. It may be assumed from the similarity in the general conformation of these three molecules that under certain conditions H_4edta may undergo a reverse tautomeric rearrangement, i.e., acquire the asymmetric structure characteristic of H_4cdta.

In the triamino complexone H_5dtpa both the tautomeric rearrangement characteristic of H_4edta and a rearrangement similar to that described above for H_4cdta are possible.

In fact, H_5dtpa molecules are combined in the crystalline state through the formation of IEHB similar to that found in H_4edta crystals. The O(2)...O(4) distance (between the carboxyl and carboxylate groups of neighbouring molecules) is equal to 2.455(3) Å with O...H* distances (1.24–1.25 Å) that are the same within the limits of experimental error. It is the acetate groups which are capable of undergoing rearrangement. Transfer of a proton from O(2) to O(4) does not, of course, disturb the trifurcate IAHB involving the ammonium H(N2) atom, but it changes the $1\bar{c}-1\bar{c}-2c'$ set of H-rings to $1\bar{c}-1c'-2\bar{c}$, which is exactly the same as the set in H_4edta.

The position of one of the carboxyl groups on the non-quaternised N(3) atom in H_5dtpa (it is determined from the values of the dihedral angles) is very similar to the position of the analogous group in H_4cdta, but while in H_4cdta the O(8) atom is merely capable of forming an O(8)...H(N1)–N(1) bond, in H_5dtpa the analogous O(7) atom forms such a bond and completes an eight-membered ring (in this case an H-ring of the type $2ec'$). It is also possible to admit the transfer of the H(O8) proton in the H_5dtpa molecule on to the N(3) atom with replacement of the bifurcated $2ec'$ system (containing a $2c'$ ring as a component) by a $2c'$ with an N(1)–H(N1)...O(7) bond and a $1c'$ ring with an N(3)–H(N3)...O(7) bond and with a suitable rotation of the carboxyl group containing the O(9) and O(10) atoms leading to the formation of a second ring of the type $1c'$ with an N(3)–H(N3)...O(9) bond (compare ring *D* in Fig. 6*b*).

Of course, these rearrangements can only be regarded as conjectural, but on the whole the possibility of the occurrence in complexones of tautomeric rearrangements relating to the position of "active" H atoms between different acidic groups of neighbouring molecules or to incomplete quaternisation of N atoms clearly exists.[4]

Table 5. List of monoamino and diamino complexone hydrohalides.

Name	Standard notation	Refs.
Iminodiacetic acid monohydrofluoride monohydrate	$[H_3ida]F\cdot H_2O$	[49]
Iminodiacetic acid monohydrochloride	$[H_3ida]Cl$	[50]
Iminodiacetic acid monohydrobromide	$[H_3ida]Br$	[50]
Iminodiacetic acid monohydroiodide	$[H_3ida]I$	[51]
Ethylenediamine-*N,N'*-dipropionic acid dihydrochloride	$[H_4eddp]Cl_2$	[39]
Ethylenediamine-*N,N,N',N'*-tetrapropionic acid dihydrochloride	$[H_6edtp]Cl_2$	[39]
Ethylenediamine-*N,N,N',N'*-tetraacetic acid dihydrochloride trihydrate	$[H_6edta]Cl_2\cdot 3H_2O$	[44]
Ethylenediamine-*N,N,N',N'*-tetraacetic acid monohydrobromide monohydrate	$[H_5edta]Br\cdot H_2O$	[39]
Phosphonomethylglycine semihydrochloride	$H_3phmg\cdot {}^1/_2HCl$	[15]
Ethylenediamine-*N,N'*-diisopropylphosphonic acid dihydrochloride dihydrate	$[H_6eddiph]Cl_2\cdot 2H_2O$	[29]

VI. Structural features of hydrohalides of complexones

The structures of hydrohalides of complexones can be used to simulate the behaviour of the corresponding complexones in strongly acidic media.[4] At the present time structural data on eight hydrohalides of aminocarboxylic complexones and two hydrohalides of aminophosphonic complexones are available (Table 5). These data relate to four hydrohalides of H_2ida (including its

hydrofluoride), dihydrochlorides of two acids containing propionate groups (H_2eddp·2HCl and H_4edtp·2HCl), and two hydrohalides of H_4edta (H_4edta·HBr·H_2O and H_4edta·2HCl·$3H_2O$), as well as phosphonomethylglycine semihydrochloride H_3phmg·½HCl and the dihydrochloride of ethylenediamine-*N*,*N*′-di(isopropylphosphonic) acid H_4eddiph·2HCl·$2H_2O$. The position of the dissociated protons of hydrohalic acids is a key feature in a discussion of the structure of compounds of this class.[4] In this case it is logical to start with the concept of a zwitterion structure of complexones in both the crystalline state and solution.

It was possible to use the structural data to establish a dependence of the crystalline structure of hydrohalides of complexones on the acidic properties of the functional groups. In cations based on weak acids the dissociated protons of the hydrohalides are clearly located on the deprotonated acid groups of the complexones, converting the molecules of the latter into cations. Strong (according to the classification of Megaw)[46] IAHB does not occur in such crystals. As an example let us examine the structure of the propionates H_2eddp·2HCl and H_4edtp·2HCl, for which precisely this type of cation-anion structure—$(H_4eddp^{2+})(Cl^-)_2$ and $(H_6edtp^{2+})(Cl^-)_2$—has been found. The cations have an open structure with the protons (from HCl) quite clearly located on the propionate groups. Although the latter could potentially participate in IAHB to form $1c'_2$ or $1c''_2$ H-rings, such rings do not occur. Even though the cations have an open structure they cannot form IEHB either between themselves or with anions.

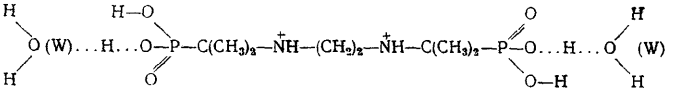
A similar cation-anion structure also occurs for hydrohalides of H_2ida, although the acetate groups have a higher acidity than propionate groups. The absence of acceptors that are suitable for forming strong IEHB, which is supported by the completely different structure of H_2ida hydrofluoride (see below), may in this case account for the low strength of IEHB.

In cations based on fairly strong acids, the dissociated protons of the hydrohalides, on the other hand, participate in the formation of strong IEHB of the type O−H...O or O−H...X, with H-rings based on IAHB being retained, although it is true that they are sometimes in combinations that are different from those in the initial complexones. Different situations can occur depending on the nature of the acid group.

Thus in H_2ida hydrofluoride quite strong IEHB of the type O−H...F has been detected between the O atom of the carboxyl group and an F^- ion [O...F distance is 2.502(2) Å], which can be attributed to the closeness of their electronegativity values (and also the van der Waals radii), i.e., to satisfy the conditions that are necessary for the formation of strong bonds.[47] A similar pattern, namely, conversion of the complexone to a cationic form with the formation of more or less strong IEHB of the type O−H...O [length 2.51(2) Å], also occurs in the case of the above-mentioned H_4edta·2HCl·$3H_2O$, the actual formula of which is $(H_6edta^{2+})(Cl^-)_2 \cdot 3H_2O$ (1:2 composition). Protonation of all of the acid groups in the complexone eliminates its zwitterion character.

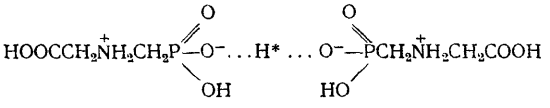
The formation of a cationic form in the hydrobromide H_4edta·HBr·H_2O (1:1 composition) occurs in a different manner. Conversion of the H_4edta molecule into an H_5edta cation does not destroy the zwitterion character of the molecule, but with this type of protonation its structure changes markedly, as has already been mentioned. The crossed eight-membered H-rings are ruptured and the central section acquires a transoid structure. At the same time the proton from dissociated HBr is not attached to any single CH_2COO^- group but is located between "semi-protonated" acetate groups of neighbouring complexones, forming strong IEHB of the type O(1)...H*...O(1)* (Fig. 5*a*) of length 2.455(5) Å with a random arrangement of two positions that are separated from each other by 0.66 Å. The resulting infinite associate that is based on this type of IEHB may be regarded as both a chain of H_5edta^{2+} cations and an alternating sequence of neutral H_4edta molecules and H_6edta^{2+} cations. It is also worth drawing attention to the fact that synthesis of this compound was carried out using excess HBr; hence the composition of the product depends on the nature of the halogen (compare with H_4edta hydrochloride).

A similar situation occurs in the structure of H_4eddiph·2HCl·$2H_2O$, where the protons from HCl are randomly distributed between monoprotonated phosphonate groups and water molecules through a strong IEHB of length 2.423(4) Å.



In this case such a structure also proves possible for a composition of 1:2 because of the increased acidity of the phosphonic group compared to the carboxyl; the pK_1 values of H_2ida and H_4idph acids are 2.54 and < 1 respectively.[48] Attachment of the proton to one of the O atoms participating in the formation of IEHB can indicate two structural variants in this case: combinations of zwitterion H_4eddiph molecules and H_3O^+ and Cl^- ions or combinations of $H_6eddiph^{2+}$ cations, water molecules, and Cl^- anions. As in the case of H_4eddiph·$2H_2O$, the complexone in H_4eddiph·2HCl·$2H_2O$ retains a semi-open structure.

In the structure of the hydrochloride H_3phmg·½HCl, the proton that has dissociated from HCl unites two H_3phmg molecules into a dimeric associate



with a strong symmetrical IEHB O...H*...O of length 2.454(3) Å. The structure in this case is quite unambiguous; the H* protons are situated at the centres of inversion and the Cl^- anions are on double axes of symmetry. In the H_3phmg hydrochloride molecule a $1c'$ H-ring is retained and the $1\overline{ph}'$ H-ring present in the structure of H_3phmg itself has opened.

The small amount of data on the crystalline structures of hydrohalides reported in this section shows that both their composition and structure are determined primarily by the nature (acidic properties) of the functional groups of the complexone and to a considerable extent by the nature of the halogen.

VII. Conclusion

The role of crystal chemical data in the resolution of problems in basic chemistry has increased very greatly during the last ten years. Structural analysis has been introduced into the very fabric of chemical research as one of its most indispensable and important components. The significance of this component is especially great for those areas of chemistry which deal with structural units—molecules, oligomers, or polymers—consisting of residues that can undergo various ways of combining with each other.

On the preceding pages only one aspect of the structural chemistry of complexones was examined—the structure of the

molecules themselves. Questions relating to the packing of the molecules in crystals, the geometric ratios with the outer-sphere ions and solvate (hydrate) molecules have been referred to only occasionally by the present authors, in mentioning only those cases of interest for their unusual nature or of importance for an understanding of possible rearrangements on going from the crystalline state to solution.

There is no doubt that there are many different aspects of the structure of such complex compounds as polyaminopolycarboxylic acids that have not been touched upon in this review. But in any case there seems to be no doubt that even incomplete structural data on complexones are not solely of independent interest. To an even greater degree they are important as a structural basis for the interpretation of their spectroscopic parameters and for developing the most effective and adequate theoretical ideas about the relationship between structural and spectroscopic properties, for a comparison of the structure of complexones and metal complexonates in crystals and in solution under different conditions (depending on the concentration and acidity), and in the end they are important for a better understanding of reaction pathways and for directed synthesis of complexonates in solving specific practical problems. The present authors, however, have quite deliberately limited the scope of this study to purely structural material, in realising that all of these problems require further varied and thorough physicochemical studies and that to supply the overall results in this area is premature for the time being.

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