# Unusual variations in the incidence of $Z' > 1$ in oxo-anion structures†

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A series of Cambridge Structural Database studies show that ionic species generally form low $Z'$ structures, even in those cases where charge assisted hydrogen bonding is a key feature, *e.g.* oxo-anion complexes. By introducing a competing π–π stacking interaction, two oxo-anion compounds are shown to crystallise with more than one molecule in the asymmetric unit, including the first hydrogen phosphate containing structure to have $Z' > 2$.

Predicting how a molecular compound is going to pack in the solid-state is an ongoing concern. The three-dimensional arrangement of molecules can have large consequences on the properties and hence the applications of a substance,[1,2] therefore the importance of being able to predict the crystal structure reliably is immeasurable. While some progress is being made in structure prediction, particularly for small organic molecules,[3] compounds which crystallise with $Z' > 1$ (*i.e.* more than one formula unit in the asymmetric unit) still prove a problem for crystallographers and theoretical chemists alike due to their increased complexity.[4,5] Recent work by Desiraju *et al.* has focussed on the nucleation process, suggesting that large $Z'$ structures may sometimes represent high energy minima in the crystallisation pathway.[6]

A search of the Cambridge Structural Database (CSD)[7,8] shows 30 806 structures (8.8%) with $Z' > 1$. Within this set, $Z'$ values range from $1\frac{1}{12}$ to 32, although values of $Z' > 4$ are rare.[9] Previous studies have shown that certain types of compounds, *e.g.* chiral molecules[10] or those containing monoalcohols[11–13] are more likely to form high $Z'$ structures, as are some naturally occurring compounds such as nucleosides, nucleotides and steroids.[10] Strong interactions such as the O–H···O hydrogen bond (which are present in these structural groups) may be responsible for some large $Z'$ structures, as motifs formed by these energetically favourable interactions do not always tesselate in a way that can be described by any of the 230 space groups. A CSD search for O–H···O containing compounds showed that structures which contain the O–H···O motif form $Z' > 1$ structures 10.0% of the time, *i.e.* more than the 8.8% of structures in the CSD as a whole (Table 1). Charge-assisted hydrogen bonds are among the strongest of their type[14] and therefore it might be expected that ionic species would show a preference for forming high $Z'$ structures. However, the CSD shows that, in fact, ionic species are

markedly *less* likely to form high $Z'$ structures than neutral species (Table 1). The counterion is obviously important in charged species and therefore we carried out a search on various common counteranions to see whether choice of anion could reduce or enhance formation of $Z' > 1$ structures for a given cation. Our studies show, however, that with the significant exception of dihydrogen phosphate ($H_2PO_4^-$) the counteranions studied all have a tendency to form structures with either $Z' = 1$ or $Z' < 1$. Formation of species with $Z' < 1$ is presumably made more likely by the symmetry of the species. Of the oxo-anions, sulfate, hydrogen sulfate and hydrogen phosphate containing compounds generally form structures with lower values of $Z'$, however dihydrogen phosphate species are more likely to form $Z' > 1$ structures by almost a factor of two compared with the average value (Table 1).

The extremely high incidence of $Z' > 1$ in dihydrogen phosphate containing compounds is partly explained by closer examination of this group. Fourteen out of the thirty-five $Z' > 1$ structures consist of protonated aliphatic monoamines (ranging from ethyl[19]- to decyl[20]-ammonium) which all pack in a very similar manner (Fig. 1), with $Z' = 2$.

The fourteen structures, which include five redeterminations, are isomorphous with the only significant difference in the structures being that the $b$ cell length increases depending on the alkyl chain length (the $a$ and $c$ cell lengths do not change significantly between structures). The dihydrogen phosphate ions form an infinite chain parallel to the $a$-axis while the alkyl chains lie perpendicular to this

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**Table 1** Frequencies of $Z'$ values in subsets of the CSD[a]

| | $n$ | $Z' < 1$ | $Z' = 1$ | $Z' > 1$ |
|---|---|---|---|---|
| CSD as whole | 349661[b] | 87035(24.9) | 232095(66.4) | 30806(8.8) |
| O–H···O | 40115 | 8599(21.4) | 27500(68.6) | 4016(10.0) |
| Ionic species | 86457 | 28061(32.5) | 52867(61.1) | 5606(6.5) |
| $PF_6^{2-}$ | 7266 | 1953(26.9) | 4834(66.5) | 479(6.6) |
| $BF_4^-$ | 5579 | 1322(23.7) | 3849(69.0) | 408(7.3) |
| $SiF_6^{2-}$ | 117 | 70(59.8) | 44(37.6) | 3(2.6) |
| $CF_3SO_3^-$ | 3150 | 671(21.3) | 2258(71.7) | 221(7.0) |
| $NO_3^-$ | 3574 | 1349(37.7) | 2046(57.2) | 179(5.0) |
| $ClO_4^-$ | 11243 | 3492(31.1) | 7094(63.1) | 661(5.9) |
| $SO_4^{2-}$ | 567 | 188(33.2) | 348(61.4) | 31(5.5) |
| $HSO_4^-$ | 133 | 34(25.6) | 91(68.4) | 8(6.0) |
| $HPO_4^{2-}$ | 73 | 16(21.9) | 55(75.3) | 2(2.7) |
| $H_2PO_4^-$ | 206[c] | 38(18.4) | 133(64.6) | 35(17.0) |
| Aliphatic polyamine salts[15,16] | 35 | 16(45.7) | 17(48.6) | 2(5.7) |
| This work | 29 | 6(20.7) | 18(62.1) | 5(17.2) |

[a] Figure in brackets is % of the whole dataset. [b] 5403 hits with $Z' = 0$ were removed and disregarded in further searches. [c] Excludes 19 redeterminations of urea phosphoric acid, CSD refcode CRBAMP,[17] $Z' = 1$.
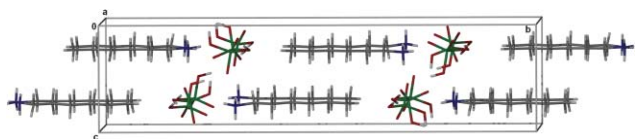
**Fig. 1** Packing (viewed down the *a*-axis) of *n*-hexylammonium hydrogen diphosphate[18] showing the interdigitated bilayer arrangement.

in an interdigitated bilayer arrangement. The bilayer is two molecules wide, leading to $Z' = 2$.

A closer look at all the dihydrogen phosphate structures showed that 152 of them ($\sim$68%) contain an $-NH_3^+$ or $-NH_2$ group, suggesting that dihydrogen phosphate has a particular affinity for this functionality.

In previous studies[15,16] we found that aliphatic polyammonium cations are excellent hydrogen bond donors and form a wide variety of extended networks with a number of counterions of different charges (and therefore different amine : anion ratios), including a number of oxo-anion structures. Of this group of 35 structures, only two (5.7%), $NH^+[(CH_2)_2NH_3^+]_3 \cdot 4Br^- \cdot H_2O$ and $[NH_3^+(CH_2)_2NH(CH_2)_2NH_3^+] \cdot SO_4 \cdot H_2O$, crystallise with $Z' > 1$, in keeping with the low values observed for ionic and oxo-anion species discussed above. There are no dihydrogen phosphate complexes in this group. One key feature of these structures is that there is no competitor to the N–H···X hydrogen bond (X = halide or oxygen) which, apart from the obvious close packing considerations, is the only significant directional inter-molecular force present. The long alkyl chains of the polyamine are flexible and this flexibility enables the molecules to orient themselves so as to maximise the hydrogen bond strength as well as keeping the molecule in a symmetric environment. Use of sterically unencumbered halide ions (as in 19 structures of this subset[16]) affords the overall structure a large degree of symmetry and therefore it is not surprising that there are a sizeable proportion ($\sim$50%) of structures in this group which have $Z' < 1$, almost twice the database average.

Frustration between close packing requirements and satisfaction of strong intermolecular interactions is thought to be a key factor in the formation of some $Z' > 1$ structures.[9] Therefore we were interested in the effect on the structures of replacing the aliphatic groups by aromatic ones, thereby introducing the possibility that C–H···$\pi$ and $\pi$–$\pi$ interactions would compete with the ionic hydrogen bonding interactions. Twenty-nine ammonium salts were therefore prepared using aromatic amines **1–4** with a variety of counteranions. A full list of compounds can be found in the supplementary information.†
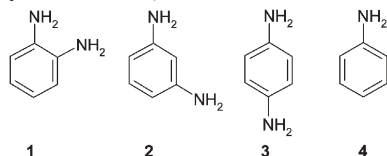


As can be seen in Table 1, there are fewer compounds with $Z' < 1$ than there are for the aliphatic polyamines and there are also five (17.2%) in this series of aromatic compounds crystallising with more than one molecule in the asymmetric unit. Of these five $Z' > 1$ compounds, two have unexpectedly large $Z'$ values ($[1^{2+}]_8 \cdot (SO_4)_6 \cdot (HSO_4)_4 \cdot 8H_2O$ **1h**, $Z' = 8$ and $[2^{2+}]_4 \cdot (HPO_4)_2 \cdot (H_2PO_4)_4$ **2c**, $Z' = 4$). These two compounds are described in detail below.

The asymmetric unit of **1h** contains eight molecules of protonated 1,2-phenylenediamine with six sulfate and four hydrogen sulfate counterions along with eight molecules of water. Unfortunately it was not possible to locate the hydrogen atoms on either the hydrogen sulfate or water molecules so the ratio of sulfate to hydrogen sulfate is assigned on a charge balance basis. The sulfate, hydrogen sulfate and water molecules form an extended 3-D network which encapsulates the protonated 1,2-phenylenediamine molecules, with additional N–H···O hydrogen bonds holding the framework together (Fig. 2).

In addition to the hydrogen bonding and as predicted there is $\pi$-stacking in the structure. The protonated 1,2-phenylenediamine molecules stack in an offset face to face arrangement with a mean centroid–centroid distance of 4.5 Å. An aryl hydrogen atom from one of the rings participates in a C–H···$\pi$ interaction with a ring from a neighbouring stack, holding the two stacks together (Fig. 3).

The aryl rings point towards each other in the centre of each pair of stacks leaving the protonated amine groups on the outside where they are readily available to participate in N–H···O hydrogen bonds. The rings are slightly tilted (mean interplane angle = 20.1°) meaning the $\pi$–$\pi$ stacking in the structure is less than ideal.[21] The driving force for the assembly of this structure is formation of the strongly interacting hydrogen bond network comprising the anions and water, leaving the 1,2-phenylenediamine stacks to fill the remaining space. The protonated polyamine moieties would typically be edge to face $\pi$-stacked,[22] however the size of the cavity (which is determined by the optimum anion···anion distance) is not sympathetic to such an arrangement and the rings are forced not only to stack in an offset face to face manner, but also to tilt with respect to one another thereby
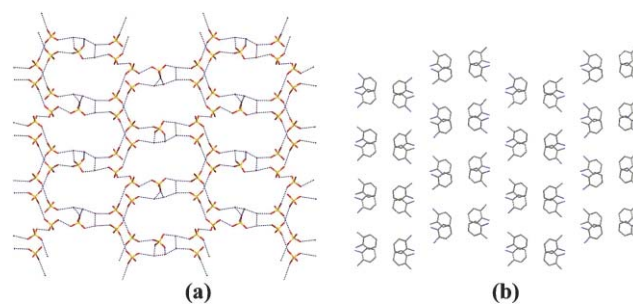


**Fig. 2** (a) The hydrogen bonded sulfate/hydrogen sulfate/water network in **1h**, viewed down the *a* axis. (b) The stacks of aromatic rings which fit into the hydrogen bonded network.
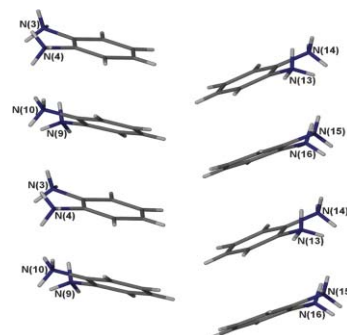


**Fig. 3** $\pi$–$\pi$ and C–H···$\pi$ stacking between aromatic rings in **1h**.
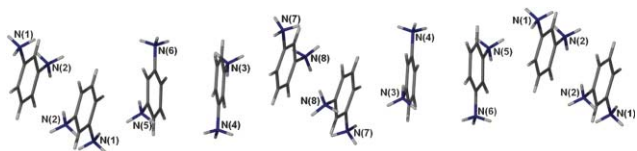
**Fig. 4** π–π Stacking between 1,3-phenylenediammonium rings in **2c** showing the rotation of protonated amine groups and the slight tilting of the aromatic rings.

lowering the symmetry of the overall structure, leading to a high value of $Z'$.

The asymmetric unit of **2c** contains four molecules of diprotonated 1,3-phenylenediamine, balanced by two phosphate and four dihydrogen phosphate counterions giving four cations per asymmetric unit, i.e. $Z' = 4$. Notably **2c** is the first $HPO_4^{2-}$ containing species found to crystallise with $Z' > 2$. The data were of sufficient quality for the hydrogens to be located and therefore it was possible to distinguish between phosphate and dihydrogen phosphate moieties, analysis of the P–O/P=O bond lengths also confirmed the assignment. As in **1h**, the anions form an extended 3-D network held together by hydrogen bonds. The compound exhibits saturated hydrogen bonding (SHB)[23] with all donor and acceptor sites involved in hydrogen bonds.

There is π–π stacking between the aryl rings of the protonated diamines as there is in **1h** but the stacking observed for **2c** is different. Here the aromatic rings are stacked face to face, with an average centroid–centroid distance of 3.8 Å, considerably shorter than the distance in **1h**. The rings are rotated with respect to each other with rotations of 240, 180 or 120° and orient themselves so that the protonated amine groups are distributed on all six sides of the stack unlike the more directional arrangement seen in **1h**. This fully staggered conformation is also in contrast to the other 1,3-phenylenediamine structures known[24] where each ring is rotated by 180° with respect to its neighbour. The rings are also tilted with respect to each other with a mean plane–plane angle of 11.9° (Fig. 4).

The stack of protonated diamines is held together by bifurcated P=O⋯H–N interactions. Each column of protonated amine molecules is surrounded by six columns of hydrogen phosphate/ dihydrogen phosphate molecules in a hexagonal type arrangement (Fig. 5).

As before, the principal interactions are in the charge assisted hydrogen bond network, here forming smaller cavities than in **1h** allowing the rings to stack with better overlap than previously observed. Again, the optimal anion⋯anion distance in the hydrogen bonded network apparently takes precedence and hence the π–π stacking of the aryl moieties is disrupted causing face to face overlap and tilted aryl rings. It is this subtle balance between the two competing intermolecular forces which we believe is responsible for the large $Z'$ values in both structures.

In summary, we have shown that charged species are less likely to form $Z' > 1$ structures and that oxo-anions, particularly sulfate, hydrogen sulfate and hydrogen phosphate, also show a general tendency to adopt low $Z'$ structures. Dihydrogen phosphate has a high incidence of $Z' > 1$ but this is partly explained by a family of protonated aliphatic monoamines which form bilayer structures with $Z' = 2$. Previous work on aliphatic polyamine salts has shown
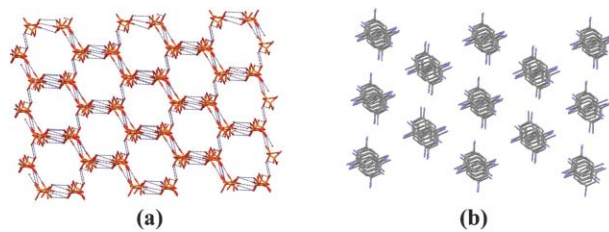


**Fig. 5** (a) The hydrogen bonded $HPO_4^{2-}/H_2PO_4^{-}$ network in **2c**. (b) The stacks of 1,3-phenylenediamine which fit into the remaining space.

that they form strongly hydrogen bonded networks with a preference for $Z' = 1/2$ or 1, however here we observe that when a competing interaction is introduced by replacing aliphatic polyamines with aromatic ones (and therefore introducing π-stacking considerations), structures with higher $Z'$ are formed more readily due to the need to balance out the two competing forces. Further work on the polymorphic behaviour of these species as well as optimising compounds to crystallise with more than one molecule in the asymmetric unit is ongoing.

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