Hydrogen Bonds between Zwitterions: Intermediate between Classical and Charge-Assisted Ones. A Case Study

Yulia V. Nelyubina, Mikhail Yu. Antipin, and Konstantin A. Lyssenko*

A. N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, 119991 Vavilov Str., 28, Moscow, Russia

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Detailed investigation of the electron density distribution function of *N*-succinopyridine in the crystal and in isolated state within Bader's Atoms in Molecules theory has been carried out to analyze the charge density and energetical aspects of zwitterionic H-bonding. By means of comparative analysis of H-bonds formed between molecular, zwitterionic, and likely charged species, it was shown that, according to the criteria of H-bonding, all these interactions do not differ from each other.

Introduction

Investigations of the nature and energetics of binding between molecular/ionic species in the condensed state occupy a central place in supramolecular and material chemistry. The most powerful tool of a specialist working in these fields is clearly the H-bond.[1−3] Its major characteristics, namely strength and directionality, provide the best control of the molecular aggregation process.[4,5] The usage of H-bonded moieties as synthons in crystal engineering[6] is especially effective when dealing with ionic[7] or charge-assisted[8,9] H-bonds, the strongest of the interactions of this type. The extreme case of them is the X−H···X-bonds (X is, e.g., oxygen) between likely charged species. On one hand, they are commonly considered as strong, since they are directional and donor to acceptor distance is even smaller than that of conventional H-bonds.[10] The structural changes occurring in the anion skeleton[11] owing to H-bonding, NMR, and IR data[12] also indicate the similarity between interanionic (i.e., H-bond between anions) and classical H-bonds. Since these two types of interactions do not differ on the fundamental scale, both of them should be able to play decisive role in the crystal packing formation. However, the opposite opinion still exists, which is based on the quantum chemical calculations of isolated associates "constructed" from H-bonded anions. According to these results, the anion−anion interactions are either absent or forced (charge-induced)[10] ones due to electrostatic reasons and thus cannot be the driving force of supramolecular organization.[13] Although recently the later statement was revised,[14] the assumption that such "bonds" do not contribute to crystal cohesion was left intact. However, since most of the chemists do consider such binding as H-bonds, it is also of interest to compare them with those between molecular species both on qualitative and quantitative levels.

To resolve the controversy between "repulsive" character of anion−anion H-bonds and their wide application as a "driving force" of supramolecular association, the detailed examination of the electron density distribution function $\rho(\mathbf{r})$,[15−17] derived from X-ray diffraction (XRD) or computational data, by means of Bader's Atoms in Molecule (AIM)[18] theory can be used. The latter approach provides information on both the full set of the attractive (bonding) interactions in crystal or model associate regardless of their nature and interaction energies[19,20] based on the presence of-bond critical points CP (3, −1) or BCPs in the $\rho(\mathbf{r})$ function. It also makes it possible to estimate the atomic energy,[18,21] which is very important when referring to H-bonding, since its change upon the interaction formation is one of the criteria allowing for the identification of the classical H-bond.[22] For instance, by means of the topological analysis of the experimental electron density,[23−26] in particular in crystalline potassium hydrogenoxalate,[27] it was shown that the interaction of anions with their likely charged neighbors is not hampered by the strong cation−anion binding but is rather the result of the local attraction. The AIM theory is, however, of no use in the case of the isolated anionic clusters, since the computational methods, in principle, fail to describe such systems.[10]

To overcome this limitation and bring together the results of two approaches concerning the interanionic interactions one has to choose as a model compound a neutral moiety, the interactions of which emulate the anion-anion H-bonds. The zwitterions containing, in particular, carboxylic and carboxylate groups, apparently, meet all these requirements: the $COOH\cdots COO^-$ interactions mediate between classical (neutral species are involved) and anionic (negatively charged fragments are bound) ones. In contrast to anion−anion binding, nobody debates the attractive character of such pseudoanionic interactions, since there is clearly no electrostatic repulsion between zwitterionic molecules. They are classified as ionic H-bonds, which lead to the formation of supramolecular associates, being very stable in the absence of additional stabilizing interactions (synthons[14]). As a result, gas-phase calculations of corresponding clusters can predict to a great extent the properties of such compounds in the solid. On the other hand, the geometrical parameters of H-bonds between zwitterions and the charge distribution over the moiety, i.e., its concentration on the COO^- group,[28] are strictly similar to those for anions. This allows one to assume that the interaction energy estimated for the zwitterions can be a good approximation to anion−anion H-bond strength. In order to demonstrate the equivalence of conventional and interanion H-bonds through the zwitterionic intermediate in the present work, we have performed the combined investigation of the *N*-succinopyridine (**1**)[39] in the solid state and in vacuo. To compare the H-bonding features of this zwitterionic system with those between the neutral and charged species, we also

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* To whom correspondence should be addressed. E-mail: kostya@xrlab.ineos.ac.ru.

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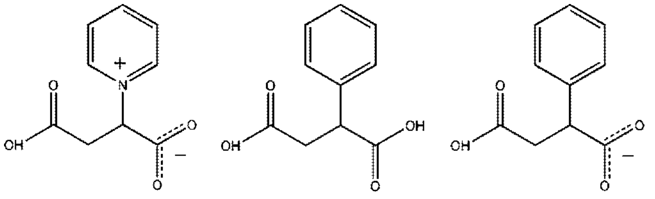
SCHEME 1: Schematic Representation of Molecule 1, the Model Acid 1a, and Its Anion 1aa



1 1a 1aa

carried out the theoretical study of the acidic analogue of **1**, which is phenylsuccinic acid (**1a**), and its anion (**1aa**) (see Scheme 1).

Experimental Section

Crystals of **1** ($C_9H_9NO_4$, M = 195.17) are orthorhombic, space group $P2_12_12_1$, at 100 K: $a = 7.6786(2)$, $b = 7.7348(2)$, $c = 14.8561(4)$ Å, $V = 882.34(4)$ Å^3, $Z = 4$ ($Z' = 1$), $d_{\mathrm{calc}} = 1.469$ g cm^{-3}, μ(Mo Kα) = 1.17 cm^{-1}, $F(000) = 408$. Intensities of 86562 reflections were measured with a Bruker SMART APEX2 CCD diffractometer [λ(Mo Kα) = 0.71072 Å, ω-scans, $2\theta < 105°$] and 5685 independent reflections [$R_{\mathrm{int}} = 0.0405$] were used in further refinement. The structure was solved by direct method and refined by the full-matrix least-squares technique against F^2 in the anisotropic-isotropic approximation. For **1** the refinement converged to wR2 = 0.0836 and GOF = 1.001 for all independent reflections (R1 = 0.0298 was calculated against F for 5287 observed reflections with $I > 2\sigma(I)$). All calculations were performed using SHELXTL PLUS 5.0.[29]

The multipole refinement was carried out within the Hansen-Coppens formalism[30] using the XD program package[31] with the core and valence electron density derived from wave functions fitted to a relativistic Dirac−Fock solution.[32] Before the refinement the C−H-bond distances were normalized to the standard value of 1.08 Å and the O−H-bond distance was fixed by 1.00 Å. The latter value was obtained by the statistical analysis of CSD (75 ordered structures, which contain the C−COOH moiety and for which the neutron data are available) and it agrees well with 1.008 Å, calculated for the isolated dimer of **1**. The level of multipole expansion was octupole for all non-hydrogen atoms. The dipole D_{10} and the hexadecapole H_{40} were refined for hydrogen atoms for more accurate description of hydrogen-bonds. The refinement was carried out against F and converged to $R = 0.0189$, Rw = 0.0196 and GOF = 0.962 for 5275 merged reflections with $I > 3\sigma(I)$. All-bonded pairs of atoms satisfy the Hirshfeld rigid-bond criteria.

The potential energy density $\nu(\mathbf{r})$ was evaluated through the Kirzhnits approximation[33] for the kinetic energy density function g(**r**). Accordingly, the g(**r**) function is described as $^3/_{10}(3\pi^2)^{2/3}[\rho(\mathbf{r})]^{5/3} + {}^1/_{72}|\nabla\rho(\mathbf{r})|^2/\rho(\mathbf{r}) + {}^1/_6\nabla^2\rho(\mathbf{r})$, what in conjunction with the local virial theorem $[2g(\mathbf{r}) + \nu(\mathbf{r}) = {}^1/_4\nabla^2\rho(\mathbf{r})]$ leads to the expression for v(**r**) and makes possible to estimate the electron energy density $h_e(\mathbf{r})$. The total electron density function was positive everywhere and the maxima of the residual electron density located in the vicinity of nuclei were not more that 0.15 eÅ^{-3}. Analysis of topology of the $\rho(\mathbf{r})$ function was carried out using the WinXPRO program package.[34]

The DFT calculations of the isolated molecule of **1** and its acidic analogues, both the neutral (**1a**) and anionic (**1aa**) ones, and corresponding dimers were performed with the Gaussian 98 program package[35] using Pbe1Pbe[36] functional which gives the best performance for hydrogen-bonding.[37] Full optimization of their geometry was carried out with the 6-311G(d,p) basis set starting from the X-ray structural data. The extremely tight threshold limits of 2×10^{-6} and 6×10^{-6} au were applied for the maximum force and displacement, respectively. The topological analysis of the computed electron densities was performed using AIMall program package.[38] The difference in molecular virial ratio is in the range of 2.793×10^{-5} to 4.586×10^{-5}.

Results and Discussion

According to the XRD data, the presence of both carboxylic and carboxylate groups in the molecule of **1** (Figure 1A) resulted in the formation of short O−H···O hydrogen-bonds (O···O 2.5219(5) Å; OHO 170.2(2)°). Since there is no other convenient proton donor or acceptor, the infinite chains "built" though them are held together only by weak C−H···O contacts (C···O 3.1443(6)−3.6503(6) Å). In contrast, the H-bond seems to be very strong, as it greatly affects the molecular geometry of **1**. According to the quantum chemical calculations (Pbe1Pbe/6-311G(d,p), see the Experimental Section) of zwitterionic monomer ($\mathbf{1_{isol}}$), the neglect of crystal packing effects leads to the geometrical changes expected in the case of classical H-bonds. They are the marked elongation of the C−O(4) bond (from 1.3088(5) Å in the solid state to 1.339 Å in the gas phase) and the shortening of C−O(1) bond down to 1.236 Å (C−O distance in crystal is 1.2657(5) Å). Moreover, the C−O bonds not involved into this interaction become shorter by ca. 0.02 Å and the dihedral angle characterizing the mutual disposition of COO$^-$ and COOH fragments increases by ca. 10°. Such distortion of molecular geometry is mainly caused by the charge redistribution in the molecule due to the H-bond formation. The latter can be confirmed by the variation of zwitterion's geometrical parameters upon its H-bonding with the neighbor molecule (Pbe1Pbe/6-311G(d,p) calculations), which follows exactly the same trends as was observed for the crystalline material. However, the large number of weak C−H···O contacts also contributes remarkably to the crystal stabilization that appears in the elongation of the O−H···O bond (O···O 2.597 Å) in isolated state.

For the description of the H-bond and all other interactions on the quantitative level, we used the detailed analysis of electron density distribution function both in the crystal of **1** and its model dimer $\mathbf{D\text{-}1_{isol}}$. The experimental distribution of the deformation electron density function (DED) in the H-bonding area (Figure 1B,C) is characterized by the expected features. The maxima of DED, attributed to electron lone pairs (Lp), are located in the vicinity of oxygens and one of them, namely the Lp of the O(1) atom, is directed toward the hydrogen atom.

The search for BCPs in isolated dimer and in crystal revealed the presence of such a point between the hydrogen and acceptor atom and the bond path linking these particular nuclei, which is the basic criterion of H-bond.[22] The topological parameters at the BCP also approve the H-bonding nature of this interaction (Table 1): the values of $\rho(\mathbf{r})$ and $\nabla^2\rho(\mathbf{r})$ are equal to 0.416 eÅ^{-3} and 5.38 eÅ^{-5} in the solid and are slightly smaller in the case of the calculated system [$\rho(\mathbf{r}) = 0.393$ eÅ^{-3}, $\nabla^2\rho(\mathbf{r}) = 3.64$ eÅ^{-5}]. It is even the case for anion−anion H-bonds in crystalline potassium hydrogenoxalate, where the $\rho(\mathbf{r})$ and $\nabla^2\rho(\mathbf{r})$ values are equal to 0.54 eÅ^{-3} and 2.03 eÅ^{-5}.[25] For comparison, the same parameters for a dimer of the model dicarboxylic acid **D-1aa** (Figure 2) with the nitrogen atom replaced by carbon (see Scheme 1) are equal to 0.355 eÅ^{-3} and 3.52 eÅ^{-5}, respectively. The minor difference in the three studied systems is, apparently, caused by the elongation of the H-bond upon

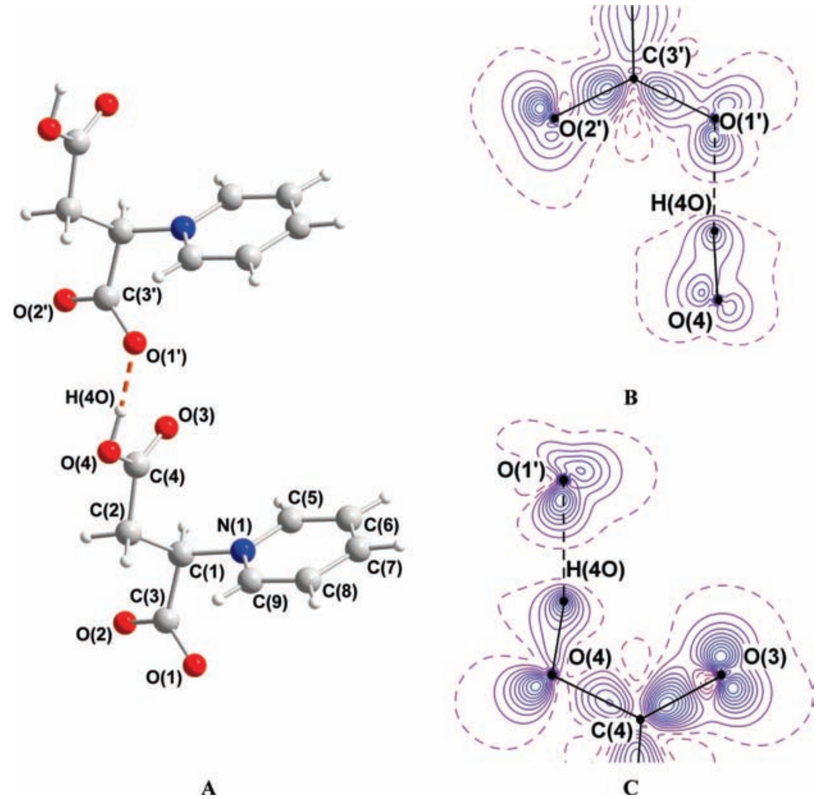


Figure 1. Fragment of crystal packing in crystalline **1** demonstrating the formation of the H-bonded dimer **D-1a** (A) and the corresponding DED distributions in the CO_2^- (B) and CO_2H (C) planes. The latter contours are drawn with 0.1 eÅ^{-3} interval, the nonpositive ones are dashed. The atoms with asterisk are obtained from the basic ones by the symmetry operation x, $y + 1$, z.

TABLE 1: Topological Parameters of Experimental and Calculated $\rho(\mathbf{r})$ Functions in BCP Corresponding to H-bond (See Figures 1−3)

system	$d_{O\cdots O}$, Å	$\rho(\mathbf{r})$, e Å^{-3}	$\nabla^2\rho(\mathbf{r})$, e Å^{-5}	$-\nu(\mathbf{r})$, a.u.	$h_e(\mathbf{r})$, a.u.	E_{cont}, kcal/mol
crystal of **1**	2.5219(5)	0.416	5.38	0.07387	−0.00901	23.2[b]
zwitterionic dimer (**D-1$_{isol}$**)	2.597	0.393	3.64	0.05961	0.01091	18.7
acidic dimer (**D-1a**)[a]	2.631	0.355	3.52	0.05194	0.00773	16.3
dianionic dimer (**D-1aa**)[a]	2.634	0.342	3.33	0.04861	0.04160	15.3

[a] The subscript "**isol**" was omitted for the dimers of **1a** and **1aa**, since only theoretical data was available for them. [b] The multipole refinement procedure in the absence of hexadecapole H_{40} term on hydrogen atoms leads to the variation of E_{cont} value within 0.2 kcal/mol.

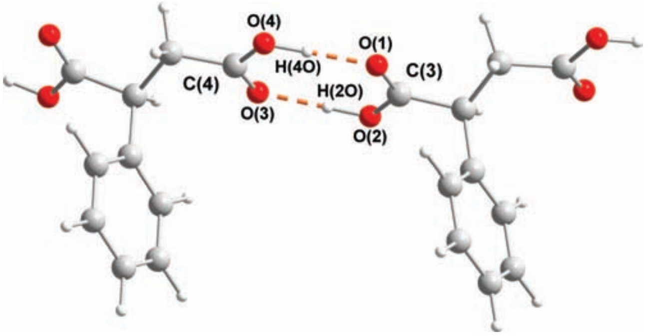


Figure 2. General view of centrosymmetric H-bonded dimer of model dicarboxylic acid **D-1a**.

the crystal-to-gas transfer. It is also accompanied by the variation of the interaction type in AIM notation. The negative electron energy density ($h_e(\mathbf{r})$)[40] at BCP of H-bond in crystal (Table 1) indicates its intermediate character,[18] whereas the same interaction in zwitterionic **D-1$_{isol}$** and acidic **D-1a** dimers is of the closed-shell type.[18] Hence, one can observe the weakening of the H-bond in going from crystalline **1** to dimer of zwitterions and that of molecules in acidic form. Its energy (E_{cont}) was estimated through the Espinosa's correlation[19,20] relating E_{cont} with the potential energy density $\nu(\mathbf{r})$ value in the corresponding BCP. The obtained values (16.3−23.2 kcal/mol) are smaller by 1 order of magnitude than those for covalent bonds, which is typical for classical H-bonds. In addition, the nearly linear correlation of interaction energy with $\rho(\mathbf{r})$ and $\nabla^2\rho(\mathbf{r})$ values at BCP also meets two necessary conditions of H-bonding.[22] The contribution of the H-bond to the dimer stabilization calculated as the difference between the energy of dimer and twice the energy of monomer (without the BSSE and ZPE correction) is also close to the one estimated though the Espinosa's approximation and is equal to 15.4 and 19.1 kcal/mol for zwitterions and acid, respectively. When examining the same parameter in the case of an isolated anion **1aa** of the model acid (Scheme 1), one notes the destabilization of the system upon its dimerization (see Figure 3) by ca. 21.2 kcal/mol according to the Pbe1Pbe/6-311G(d,p) calculations. However, the topological analysis of corresponding electron density

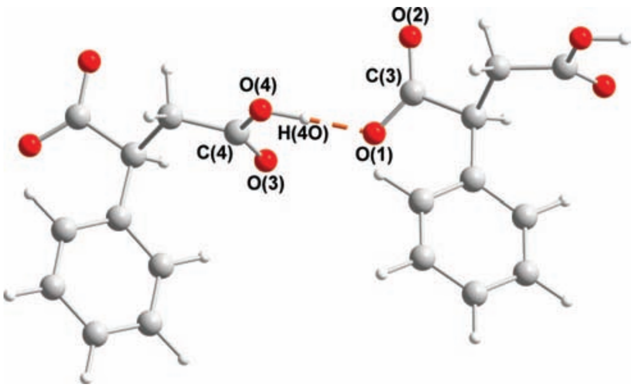


Figure 3. General view of centrosymmetric H-bonded dimer of anions of model dicarboxylic acid **D-1aa**.

distribution function revealed the BCP and bond path along the O···H line (Figure 3). Although their presence cannot be regarded as the unambiguous indicator of the bonding nature of this interaction, since the dianionic dimer in isolated state is not the "realistic" system,[41] its instability is not due to the repulsive component of the anion−anion H-bond.[27,42] Topological characteristics at this BCP ($\rho(\mathbf{r})$ and $\nabla^2\rho(\mathbf{r})$ are 0.342 eÅ^{-3} and 3.33 eÅ^{-5}) are very similar to those in the above crystal and two stable dimers **D-1$_{isol}$** and **D-1a**. The slight decrease of the interanionic interaction energy, which is equal to 15.3 kcal/mol (Table 1), is a result of the repulsion between likely charged centers in this associate and, apparently, of the H-bond elongation (O···O 2.634 Å).

In line with the topological parameters at BCP of this interaction, the H-bond in these systems exhibits a significant component of electrostatic character. As a result, when speculating about its strength one also has to take into account net charges of the interacting fragments. To calculate the corresponding atomic charges (q_{at}), we integrated $\rho(\mathbf{r})$ over $\mathbf{\Omega}$, the atomic basins surrounded by zero-flux surface.[18] The obtained values reflect the nonzwitterionic nature of **1**, since the positive charge is not concentrated at the nitrogen site ($q_{at}(N)$ is −0.88 e in the crystal and −1.25 and −1.24 e for isolated monomer and dimer of **1**) but is rather delocalized over the molecule. The oxygen atoms also bear the negative charge, unequally distributed between them (Table 2). One notes that, although the H-bonding should lead to the substantial electron density accumulation on proton donor and acceptor, the charge at the O(1) atom of carboxylate fragment in solid **1** is only −0.80 e. The q_{at} values for the remaining oxygens vary from −0.97 to −0.82 e with O(4) atom being the most negatively charged. For the isolated dimers of both the zwitterionic and acidic forms (**D-1$_{isol}$** and **D-1aa**) the expected trend is observed; the charge on oxygens involved in the H-bond (see Table 2) decreases upon its formation. This partly holds even in the case of the dianionic **D-1aa** system, where the donor oxygen becomes more negatively charged by ca. 0.1 e, followed by a slight increase of charge on the acceptor atom.

The difference between q_{at} values in the solid and in model systems can be due to the carboxylate group behaving as a whole moiety owing to electron density delocalization as well as the consequence of weak interactions. Indeed, the BCPs were found for a number of C−H···O and even C···C (or $\pi\cdots\pi$) and H···H interactions in the crystal of **1** (Table 1 of SI). They are, apparently, responsible for the additional charge redistribution over the molecule, causing a considerable charge transfer to O(2) and O(3) atoms. Their energy, which does not exceed 3.1 kcal/mol per one C−H···O contact, gives 17.8 kcal/mol in total. It is only slightly smaller than that for the H-bond, and thus these interactions contribute to the crystal cohesion about half of the lattice energy, which is 41.0 kcal/mol (calculated as the sum of energies of all independent interactions in crystal; for more details see ref 43). The further examination of atomic charges revealed that both the carboxylic and carboxylate groups of **1** in the crystal are negatively charged (−0.15 and −0.22 e, respectively). This allows one considering such interactions between zwitterions "pseudoanionic H-bonds", since the latter display the qualitatively similar distribution of charge density. For instance, the summation of q_{at} values for the carboxylic and carboxylate groups of hydrophthalate moiety in its potassium salt leads to −0.47 and −0.57 e, respectively.[26] It also persists for the zwitterions of **1** in the gas phase, where the charge of COO(H) fragments is −0.15 and −0.60 e in the monomer **1$_{isol}$** and −0.14 and −0.62 e for the dimer **D-1$_{isol}$**. The corresponding values for the model anionic system are slightly smaller but of the same order of magnitude. The overall charge of the carboxylic and carboxylate groups in the isolated anion is −0.23 and −0.76 e; upon the dimerization it increases up to −0.19 and −0.75 e. Such variation of interacting fragments charge in the crystal and in the model systems should increase the electrostatic repulsion and additionally determine the difference in H-bond strength, although its weakening in the case of neutral associates is, apparently, governed by the geometrical changes. Since the likely charged moieties participate in this interaction, the H-bond between zwitterions closely resembles the anion−anion bonding. On the other hand, it does not differ much from the classical H-bond: the same parameter for two COOH groups in the model monomer or dimer of acid under study is in the range of −0.14 to −0.13 e.

Another feature that they also have in common is the loss of charge on the hydrogen atom and the decrease of its volume upon H-bonding. The carboxylic hydrogen atom in both the zwitterionic and acidic systems becomes smaller in volume and more positively charged. The values of q_{at}(H) and V_{at}(H) change from 0.60 e and 3.17 Å^3 to 0.65 e and 1.49 Å^3 for the zwitterions and from 0.59 e and 3.18 Å^3 to 0.65 e and 1.56 Å^3 for the acid. The latter, for instance, correlates with the elongation of the H-bond and, thus, with the decrease of its energy in the case of the acidic dimer. In addition, the H-bond formation should cause the decrease in the dipolar polarization of this hydrogen atom ($|M(\mathrm{H})|$). In both cases the $|M(\mathrm{H})|$ value changes from 0.153 to 0.094 au in the zwitterionic dimer and from 0.154 to 0.100 au in its acidic analogue, thus meeting another necessary condition of H-bonding.[22] The formation of the dimer from the model anions likewise lead to the increase in q_{at}(H) from 0.57 to 0.65 e and the decrease in V_{at}(H) and $|M(\mathrm{H})|$ from 3.37 to 1.65 Å^3 and from 0.167 to 0.101 au, respectively. The H(4O) atom in the crystal is also characterized by the largest charge value (+0.45 e) and smallest atomic volume (2.21 Å^3) among all of the hydrogen atoms. This allows one to further attribute this type of interactions between the zwitterions and, indirectly, between anions to conventional H-bonds.[22]

Another important criterion left concerns the energetical aspects of interactions.[22] It is already well-known that the application of AIM theory to the analysis of the electron density distribution function can provide the atomic energy.[18] Although its absolute value obtained on the basis of the XRD or quantum chemical data is of no use, the difference between the energy of an atom in complex and that in the free molecule (ΔE_{at}) contains the information on the nature and strength of the intermolecular interctions.[44] In particular, the characteristic of H-bonds, for which no exception has been found so far, is the

TABLE 2: Selected Atomic Charges (e) in Crystal (1), Isolated Zwitterion (1_{isol}), and Its Dimer (D-1_{isol})[a], Monomeric (1a), and Dimeric (D-1a) Forms of Model Acid, and Isolated Anion of the Acid (1aa) and Its Dimer (D-1aa)

atoms	**1**	1_{isol}	D-1_{isol}	1a[b]	D-1a	1aa	D-1aa
O(1)	−0.80	−1.20	−1.22	−1.18	−1.20	−1.25	−1.23
O(2)	−0.82	−1.20	−1.18	−1.12	−1.18	−1.24	−1.23
O(3)	−0.90	−1.19	−1.20	−1.18	−1.20	−1.20	−1.21
O(4)	−0.97	−1.12	−1.20	−1.12	−1.18	−1.11	−1.21
H(4O)	+0.45	+0.60	+0.65	+0.59(+0.60)[c]	+0.65(+0.66)[c]	+0.57	+0.65
C(3)	+1.40	+1.79	+1.77	+1.57	+1.59	+1.73	+1.71
C(4)	+1.28	+1.56	+1.61	+1.57	+1.59	+1.51	+1.58

[a] The values are given for the fragments directly participating in the H-bond formation as shown in Figures 2 and 3. [b] The subscript "**isol**" was omitted for the monomers and dimers of **1a** and **1aa**, since only theoretical data was available for them. [c] In parenthesis the values for H(2O) atom of model acid are given.

TABLE 3: Difference of Selected Atomic Energies (kcal/mol)[a] in Isolated Zwitterion (1_{isol}), Acid (1a), and Anion (1aa) and Corresponding Dimers (D-1_{isol}, D-1a, and D-1aa)

atoms	D-1_{isol}−1_{isol}	D-1a−1a[b]	D-1aa−1aa
O(1)	+1.88	+9.37	−7.28
O(2)	−9.70	−44.88	+1.77
O(3)	+8.32	+7.93	+9.17
O(4)	−35.70	−44.67	−37.40
H(4O)	+27.66	+25.71(+26.06)[c]	+38.71
C(3)	−12.88	+13.69	−6.87
C(4)	+25.80	+13.99	+37.81

[a] The values are given for the fragments directly participating in the H-bond formation as shown in Figures 2 and 3. [b] The subscript "**isol**" was omitted for the monomers and dimers of **1a** and **1aa**, since only theoretical data was available for them. [c] In parenthesis the values for H(2O) atom of model acid are given.

destabilization of hydrogen atom due to H-bonding.[22] This was also observed for the zwitterionic as well as acidic systems under study (Table 3): the ΔE_{at} values are positive in both cases and are very close to each other (25.71 vs 27.66 kcal/mol), which agrees with the loss of charge on hydrogen. On the other hand, the gain of charge by the interacting oxygen atoms should cause the decrease in their energy. Indeed, in the case of charged associate **D-1aa**, although the dimerization of anions leads to the system destabilization, the O(1) and O(4) atoms gain 7.3 and 37.4 kcal/mol (Table 1), respectively. Two other oxygens were found to be destabilized by 1.8 and 9.17 kcal/mol. The greater loss of energy (37.8 kcal/mol) was observed for the carboxylate carbon, while the absolute E_{at} value for the C(3) atom increases by 6.9 kcal/mol. This agrees well with the opposite change of their charges upon H-bonding. Such energetical difference between the carbon atoms resulted in the sensible destabilization of COO fragment (by 9.6 kcal/mol) of carboxylate group, that in addition to the increase in hydrogen energy destabilizes the anionic dimer. In contrast, when comparing the atomic energies of four oxygens in the crystalline **1**, one notes that the O(1) and O(4) atoms, involved in H-bond, exhibit the smallest and highest absolute E_{at} values, respectively. The other two oxygens (O(2) and O(3)) are stabilized by 13.2 and 45.9 kcal/mol with respect to the O(1) atom. The obtained energy differences for zwitterionic monomer-to-dimer transfer also show that only the oxygen atom acting as an acid in the formation of this interaction is stabilized. However, it can be hardly considered as an indicator of the fundamental distinction between zwiterrionic and classical H-bonds, since the dimerization of acid resulted in similar values. Moreover, in the same way it changes the energy of donor and acceptor of proton in formaldehyde, both in its centrosymmetric and asymmetric dimers.[45] The other feature the acidic and zwiterionic forms of **1** have in common is the stabilization of O(2) atom, which is clearly the consequence of the additional H-bonding or of the delocalized character of the carboxylate group. This fact together with the substantial stabilization of O(4) atom are responsible for the overall decrease in the energy of both systems accompanying H-bond formation.

Conclusion

The H-bonds between zwitterions, closely resembling the corresponding anion−anion interactions on the geometrical and charge density distribution level, are directional, strong and for sure contribute greatly to the crystal/cluster cohesion, as all the hydrogen bonds do. When estimating this contribution, instead of the difference between the energy of dimer and that of monomer or, at least, in addition to it, one should use Espinosa's correlation. The latter seems to be the best choice in the case of charged systems, for which the "energy difference-based" approach predicts the destabilizing character of the interionic binding. The Espinosa's correlation scheme not only provides the interaction strength with sufficient accuracy, as appears from the semiquantitative (within several kilocalories per mole) agreement between the values obtained by both methods in the case of neutral species, it also does not fail to describe the attractive nature of H-bonds between likely charged ions that are considered truly stabilizing by a majority of chemists. Indeed, although the negative charge on both interacting groups of zwitterions **1** in the crystal and in the isolated state has to destabilize the system, according to the proposed criteria of H-bonding,[22] the described interactions are, in fact, the classical H-bonds. Since the H-bonding between anions is analogous to that of zwitterions, it should not be distinguished from the conventional H-bonds, especially considering the crystal packing effects (C−H···O contacts, cation−anion bonds, etc.), which ensure the withdrawal of the excessive charge from the carboxylate moiety and, thus, compensate for its destabilization. As a result, one has to take into account the H-bonding possibilities of partially deprotonated polycarboxylic acid anions while constructing materials of desired architectures.

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Supporting Information Available: Additional experimental information in tables and CIF files. This material is available free of charge via the Internet at http://pubs.acs.org.

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