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Anion–π Interactions in Cyanuric Acids: A Combined Crystallographic and Computational Study

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Abstract: Several structures of π complexes of isocyanuric acid and of several thio derivatives with anions have been computed by using high level ab initio calculations. The nature of the complexes has been studied by means of the method of molecular interaction potential with polarization (MIPp) and Bader's theory of atoms-in-molecules. These molecules form favorable complexes with anions and can be used as binding units for building receptors for the molecular recognition of anions. In several cases, the anion–π interaction has been demonstrated experimentally by means of X-ray crystallography.

Keywords: ab initio calculations · isocyanuric acid · pi interactions · receptors

Introduction

Noncovalent interactions between molecules are weak binding forces that control many biological functions. Nowadays, noncovalent interactions are used for the synthesis of large supramolecular aggregates in solution with specific chemical properties.[1] They are key forces in noncovalent synthesis,[2] self-replication,[3] supramolecular catalysis,[4] and functional noncovalent devices.[5] In addition, molecular recognition of substrate molecules (guests) by synthetic receptors (hosts) continues to be a prominent application of supramolecular chemistry.

In spite of the fact that anion coordination chemistry[6] is less developed than cation coordination chemistry, it is one of the most relevant and challenging fields of research within host–guest chemistry.[7] Important applications of the molecular recognition of anions are catalysis,[8] analytical chemistry,[9] and reactions templated by anions.[10] Additionally, it controls important biochemical processes, such as transport and binding of amino acids and nucleotides.

Interactions involving aromatic rings are important binding forces in both chemical and biological systems and they have been reviewed by Meyer et al.[11] A molecular interaction between an electron-deficient π-electron system of aromatic compounds and an anion is an important topic that has attracted considerable attention in the last three years. We[12] and others[13] have demonstrated theoretically that the interaction between π-electron-deficient aromatic rings and anions is energetically favorable. Experimentally, anion–π interactions have been shown between s-triazine and chloride[14] and between s-tetrazine and the AsF_6^- ion,[15] both in the solid state. Three important reports have been recently published concerning interactions in solution. First, halide recognition through aromatic receptors based on anion–π interactions.[16] Second, an aromatic anion receptor based on s-triazine and pyridine rings, which is able to encapsulate two chloride anions.[17] Third, anion binding at the peripheral nitrogen of a C_6F_5-substituted N-confused porphyrin,[18] which gives unusually high association constants that are attributed to an anion–π interaction between the anion and the C_6F_5 aromatic system. The anion–π interaction is, in general, dominated by electrostatic and ion-induced polarization forces.[12a,c] The electrostatic part is rationalized empha-

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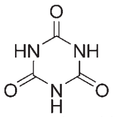
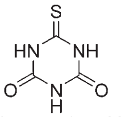
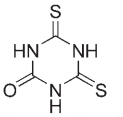
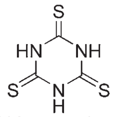
sizing the permanent and positive quadrupole moment (Q_{zz}) of the aromatic system and the anion-induced polarization part depends on the molecular polarizability of the system.[12c]

In this manuscript we report on high-level ab initio calculations of several complexes of isocyanuric (**ICA**), thiocyanuric (**TIA**), dithiocyanuric (**DIA**), and trithiocyanuric (**TTA**) acids with several anions (F^-, Cl^-, and Br^-). These


cyanuric acid
(**ICA**)
Q_{zz}=6.96 B
α=35.515 a.u.


thiocyanuric acid
(**TIA**)
Q_{zz}=6.49 B
α=44.966 a.u.


dithiocyanuric acid
(**DIA**)
Q_{zz}=5.87 B
α=54.331 a.u.


trithiocyanuric acid
(**TTA**)
Q_{zz}=5.15 B
α=63.755 a.u.

molecules have large and positive permanent Q_{zz} values; therefore, they are good candidates for establishing a favorable π interaction with anions. They have potential uses in the molecular recognition of anions and in drug design, as a Lewis acidic group.[19] We also analyze the nature of the interaction using the molecular interaction potential with polarization MIPp method,[20] which is a convenient tool for predicting binding properties.[21] Additionally, we report the synthesis and crystallographic structural data of several derivatives of **TIA** and **DIA**, which reveal interesting noncovalent interactions in the solid state, including anion–π contacts between either chloride, bromide, or iodide anions and the ring.

Computational Methods

The geometries of all complexes included in this study were fully optimized at the MP2(full) level using the 6–31++G** basis set by means of the Gaussian 03 program.[22] No symmetry constrains were imposed in the optimizations except for the complex of **DIA** with fluoride. In this case the minimum corresponded to the nucleophilic attack of the anion at the carbon atom of the ring that is bound to the oxygen atom. In the optimization of this complex the anion was fixed along the line perpendicular to the center of the ring. The binding energies were calculated with and without the basis set superposition error (BSSE) by using the Boys–Bernardi counterpoise technique[23] and zero-point energy (ZPE) corrections. Frequency calculations at the same level confirmed that the structures are at their energy minima except for fluoride complexes of **DIA**, **TIA** and **TTA** (F^- complexes of **TIA** and **TTA** were optimized without symmetry constrains), which have been included in the study for comparison purposes. The true minima correspond to the nucleophilic attack of the fluoride to the ring. This behavior has been previously observed in fluoride complexes with s-triazine[13b] and hexafluorobenzene.[12a,13c] The topological analysis of the charge density ρ(r) distribution and properties of critical points (CP) were determined by using the atoms-in-molecules (AIM) method,[24] which provides an unambiguous definition of chemical bonding[25] by means of the program AIM2000[26] by using the MP2/6–31++G** wave function. The Q_{zz} values of **ICA**, **TIA**, **DIA**, and **TTA** were computed by using the CADPAC program[27] at the MP2/6–31G* level, since previous studies[28] demonstrated that quantitative results are obtained at this level of theory. Molecular polarizabilities (α) were computed at the MP2(full)/6–31++G** level of theory by using the Gaussian-03 program.

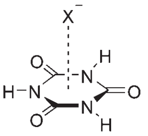
Results and Discussion

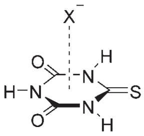
Table 1 reports the energies and equilibrium distances obtained for complexes **1**–**12** at the MP2(full)/6–31++G** level of theory. For all complexes the interacting energy is large and negative, indicating that the interaction is favorable. Moreover, the equilibrium distances and binding energies are similar for the **ICA**, **TIA**, **DIA**, and **TTA** complexes. For instance, the binding energy of the four chloride complexes is approximately constant (within the range −15.5 to −14.7 kcal mol^{-1}), indicating that the number of oxygen atoms substituted by sulfur atoms in the molecule does not affect significantly the binding energy. Table 1 also reports selected electron-density topological properties of the complexes. A common feature of **ICA**, **TIA**, **DIA**, and **TTA** upon complexation of the anion is the formation of a cage CP (ρ(3,+3)), located along the line connecting the anion with the center of the ring. It has been demonstrated that the electron charge density at the cage CP can be used as a measure of the strength of the interaction.[12c] The values of ρ(3,+3) given in Table 1 indicate that there is a relationship between the interaction energy and the electron charge density at the cage CP. For instance, fluoride complexes **1**, **4**, **7**, and **10** have greater ρ(3,+3) values than the rest of the complexes in agreement with the computed binding energies, which are approximately 11 kcal mol^{-1} more

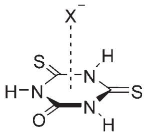
Table 1. Binding energies (E in kcal mol^{-1}) with and without the basis set superposition error (BSSE) and ZPE corrections and equilibrium distances (R_e in Å) at MP2(full)/6–31++G** level of theory. The superscripted value indicates the number of imaginary frequencies (NImag).

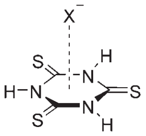
	E	E_{BSSE}	$E_{BSSE+ZPE}$	R_e	$10^2\rho(3,+3)$
1 (**ICA**···F^-)	−32.28	−27.95	-26.85^0	2.190	1.2834
2 (**ICA**···Cl^-)	−22.81	−16.45	-15.50^0	2.848	0.8919
3 (**ICA**···Br^-)	−25.18	−15.04	-14.27^0	2.979	0.8746
4 (**TIA**···F^-)	−33.09	−28.28	-27.27^1	2.197	1.2626
5 (**TIA**···Cl^-)	−23.16	−16.45	-15.63^0	2.852	0.8871
6 (**TIA**···Br^-)	−25.81	−15.13	-14.40^0	2.981	0.8763
7 (**DIA**···F^-)	−32.90	−27.67	–[a]	2.168	1.2446
8 (**DIA**···Cl^-)	−23.18	−16.33	-15.39^0	2.865	0.8729
9 (**DIA**···Br^-)	−26.15	−15.00	-14.27^0	2.988	0.8714
10 (**TTA**···F^-)	−31.35	−26.34	-25.13^1	2.255	1.2068
11 (**TTA**···Cl^-)	−22.83	−15.81	-14.69^0	2.887	0.8530
12 (**TTA**···Br^-)	−26.25	−14.61	-13.73^0	2.999	0.8602

[a] This complex has been optimized imposing symmetry constrains.


1, X=F
2, X=Cl
3, X=Br


4, X=F
5, X=Cl
6, X=Br


7, X=F
8, X=Cl
9, X=Br


10, X=F
11, X=Cl
12, X=Br

negative (E_{BSSE}) than the chloride and bromide complexes. Moreover, the $\rho(3,+3)$ values obtained for chloride and bromide complexes are similarly in agreement with their E_{BSSE} values.

To analyze the physical nature of the anion–π interaction in **ICA**, **TIA**, **DIA**, and **TTA** complexes and determine whether polarization and electrostatic terms are important, we have computed their contributions to the total interaction energy with the MIPp method. This method is an improved generalization of the molecular electrostatic potential (MEP) in which three terms contribute to the interaction energy: 1) an electrostatic term identical to the MEP,[29] 2) a classical dispersion–repulsion term, and 3) a polarization term derived from perturbation theory.[30] Thus, it provides a natural partitioning of the interaction energy into intuitive components. Calculation of the MIPp of **ICA**, **TIA**, **DIA**, and **TTA** interacting with Cl^- was performed by using the HF/6–31++G** wavefunction by means of the MOPETE-98 program.[31] The ionic van der Waals parameters for Cl^- were taken from the literature.[32]

We have explored the electrostatic (E_e), polarization (E_p), van der Waals (E_{vw}), and total (E_t) interacting energies when a chloride ion approaches the **ICA**, **TIA**, **DIA**, and **TTA** molecules perpendicularly to the center of the ring. The results presented in Table 2 underline the importance of the electrostatic and polarization contributions. The former dominates the interaction in all cases; however as the number of oxygen atoms replaced by sulfur atoms increases, the importance of the latter (polarization contribution) also increases, which is in agreement with the computed polarizabilities of the acids. The MIPp interaction energies computed at the equilibrium distance of the optimized complex (MP2(full)/6–31++G**) agrees favorably with the energetic results of Table 1 (without the BSSE correction). These values are also included in Table 2 and validate the predictive utility of the MIPp method.

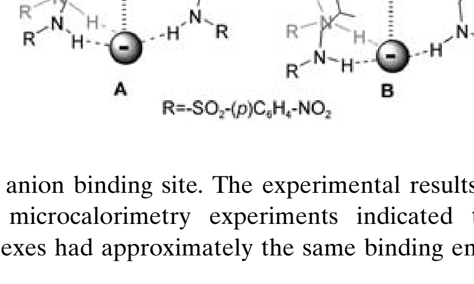
Table 2. Contributions to the total interacting energy (kcal mol^{-1}) calculated with MIPp for **ICA**, **TIA**, **DIA**, and **TTA** interacting with Cl^- at several distances (Å) from the center of the ring.

Distance	E_e	E_p	E_{vw}	E_t	E (MP2)
ICA					
1.5	−50.04	−40.67	1509.63	1419.10	
2.0	−31.44	−22.30	166.72	112.88	
2.5	−21.14	−12.25	16.58	−16.81	
2.85[a]	−16.38	−8.23	1.50	−23.12	−22.81
3.0	−14.75	−7.00	−0.39	−22.14	
3.5	−10.59	−4.20	−1.60	−16.38	
TIA					
1.5	−50.40	−45.29	1524.63	1428.94	
2.0	−31.48	−25.30	167.69	110.91	
2.5	−21.01	−14.17	16.56	−18.62	
2.85[a]	−16.20	−9.66	1.40	−24.25	−23.16
3.0	−14.55	−8.25	−0.48	−23.29	
3.5	−10.36	−5.03	−1.68	−17.07	
DIA					
1.5	−49.43	−50.30	1581.31	1481.58	
2.0	−30.51	−28.51	171.93	112.91	
2.5	−20.13	−16.22	16.83	−19.52	
2.87[a]	−15.17	−10.93	1.01	−25.09	−23.18
3.0	−13.79	−9.58	−0.56	−23.93	
3.5	−9.71	−5.91	−1.77	−17.39	
TTA					
1.5	−51.02	−54.60	1568.77	1463.15	
2.0	−31.36	−31.35	171.05	108.35	
2.5	−20.56	−18.06	16.65	−21.97	
2.89[a]	−15.18	−12.04	0.58	−26.63	−22.83
3.0	−13.98	−10.79	−0.67	−25.44	
3.5	−9.77	−6.72	−1.85	−18.34	

Additionally, we have constructed two-dimensional (2D) MIPp energy maps for **ICA**, **TIA**, **DIA**, and **TTA** in a plane located 2.76–2.80 Å above the molecular planes (see Figure 1) to explore the suitability of the molecules to be used as binding blocks for constructing anion receptors. The 2D-MIPp maps are topologically very similar. An extended region above the molecular plane can be observed at which the interaction of Cl^- with the cyanuric acid and their thioderivatives is favorable. This result confirms the suitability of these units as building blocks for the construction of anion-binding receptors. The location of the global MIPp minimum is represented by a star in Figure 1.

Curiously, the computed binding energy of the complexes does not depend on the number of sulfur atoms present in the system. It depends only on the anion. This result is due to a compensating effect of two main factors, that is, the electrostatic and the anion-induced polarization contributions. The polarizability of the ring increases with the number of sulfur atoms, and it is known that there is a direct relationship between the molecular polarizability perpendicular to molecular plane (α) and the polarization contribution to the total interaction energy.[12c] In contrast, the Q_{zz} of the ring system decreases with the number of sulfur atoms. These compensating effects lead to the result that the binding energy computed for a given anion interacting with either **ICA**, **TIA**, **DIA**, or **TTA** is approximately constant. A representation of the variation of Q_{zz} and α depending on the number of oxygen atoms replaced by sulfur atoms is shown in Figure 2 and the opposite behavior of both parameters can be clearly appreciated.

It is worth mentioning that a very interesting work of Hoffmann et al.[33] deals with the effect of conformational preorganization on the binding properties of several anion receptors. In that study, they used receptors based on a isocyanuric platform, in which three hydrogen-bonding donor groups were attached (complexes **A** and **B**) and some efforts were undertaken to clarify whether this platform is an additional anion binding site. The experimental results obtained using microcalorimetry experiments indicated that both complexes had approximately the same binding energy, and,



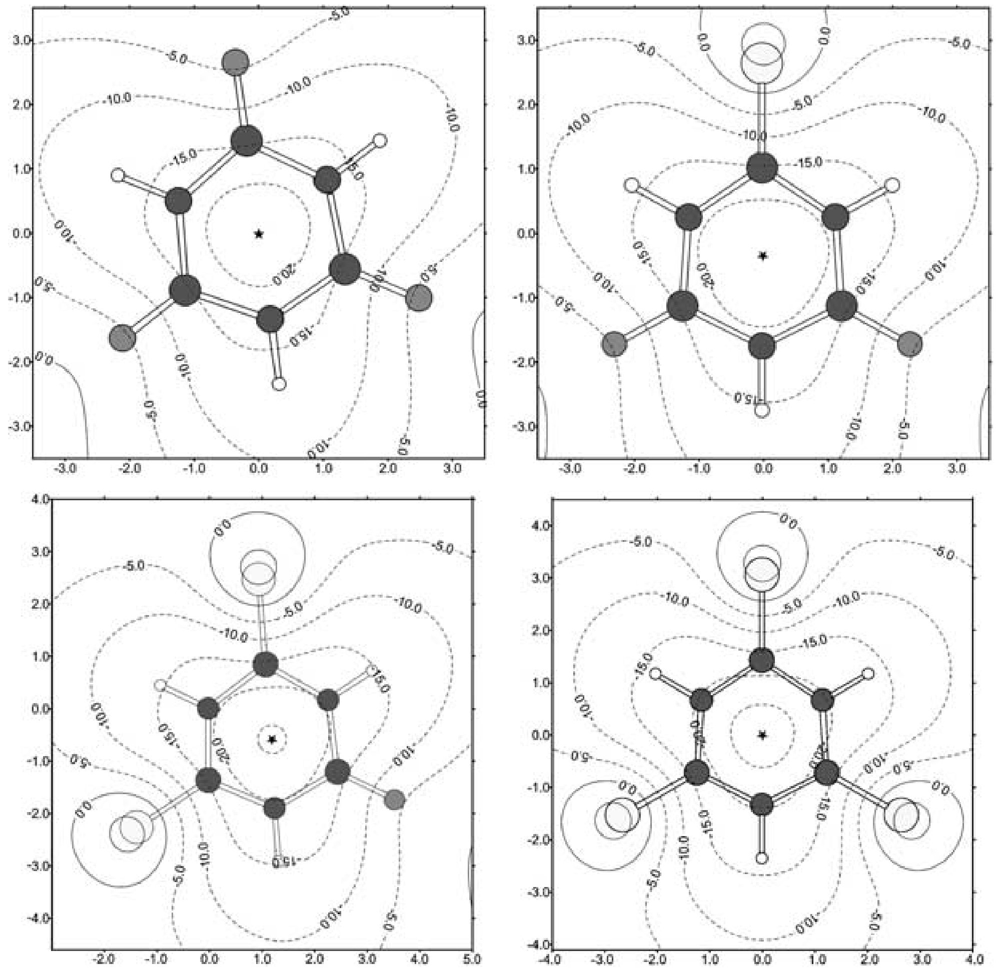


Figure 1. 2D-MIPp energy maps of **ICA** (left, top), **TIA** (right, top), **DIA** (left, bottom), and **TTA** (right, bottom) interacting with Cl⁻. The maps are computed parallel to the molecular plane at the distance where the MIPp minimum is located. The MIPp minimum is represented by a star.

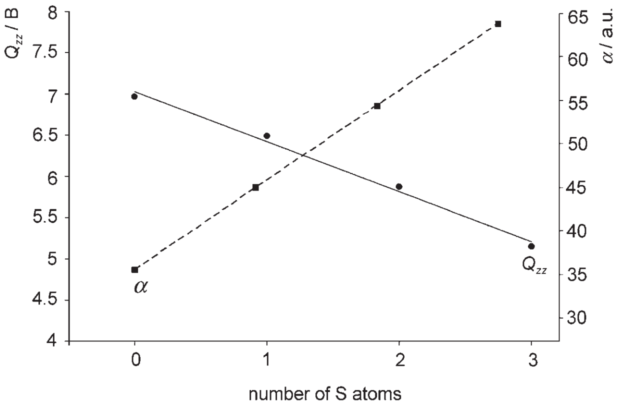
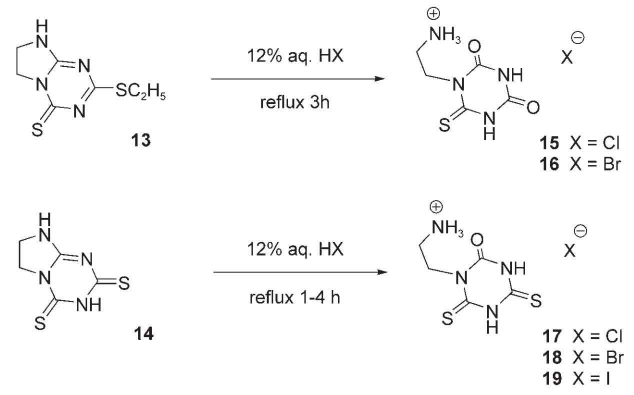


Figure 2. Plot of the regression between the molecular polarizability (α) and the Q_{zz} of **ICA**, **TIA**, **DIA**, and **TTA** with the number of sulfur atoms present in the systems.

thus, the potential electrostatic attraction of chloride by the isocyanuric platform was not reflected by the experimental data. These results, however, are in agreement with our theoretical results. The MIPp data presented in Table 2 reflect that there is a wide range of distances over which the interacting energy is large and negative. For instance, the MIPp value for the interaction of **ICA** with chloride placed 2.5 Å apart from the ring centroid is almost the same as that computed at the distance of 3.5 Å (≈ -16 kcal mol^{-1}) and, consequently, a likely explanation is that the effect of the isocyanuric platform on the anion binding in complexes **A** and **B** is similar and does not allow to differentiate one with respect to the other.

To obtain experimental evidence of the ability of isocyanuric acids to interact favorably with anions, we have synthesized derivatives of **TIA** and **DIA** with a flexible 2-ethyleneamine arm attached to the *s*-triazine ring. The one step synthesis of compounds **15**–**19** is outlined in Scheme 1. The starting products 2-ethylthio-7,8-dihydroimidazo[1,2-*a*]-1,3,5-triazine-4(6*H*)-thione (**13**) and 7,8-dihydroimidazo[1,2-*a*]-1,3,5-triazine-2,4(3*H*,6*H*)-dithione (**14**) were prepared according to a previous literature procedure.[34] A suspension of either **13** or **14** in 12 % aqueous HX (X = Cl, Br, I) acid was refluxed for 1–4 h. After cooling to ambient temperature, prismatic colorless crystals of products **15**–**19** suitable for X-ray analysis were obtained by slow evaporation.



Scheme 1. Synthesis of halide salts **15**–**19**.

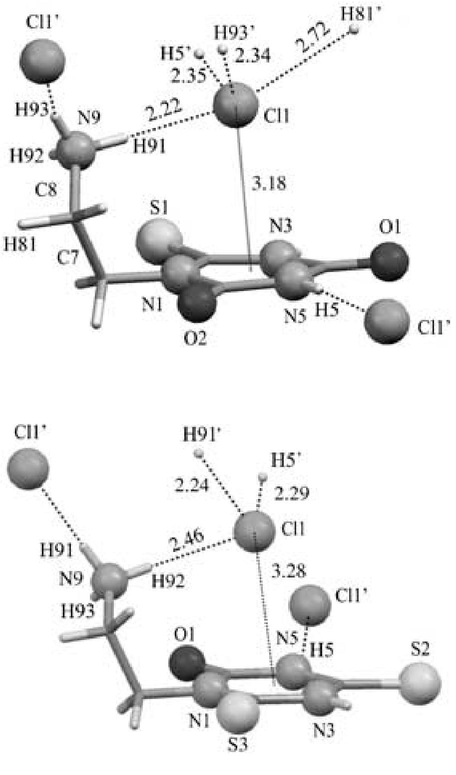


Figure 3. Short contacts of the Cl$^-$ ion in crystal structures of **15** (top) and **17** (bottom). Distances are given in Å. Primed atoms belong to symmetry-related molecules.

The X-ray crystal structure analysis of **15** revealed some very interesting features. The organic cation, which has several hydrogen-bond proton–donor and proton–acceptor functionalities, adopts a conformation that allows one of the N–H hydrogen atoms from the ammonium moiety to bind to the Cl$^-$ ion located nearly above the center of the electron-deficient thioisocyanurate ring (Figure 3, top). The anion is situated at a distance of 3.15 Å from the ring best plane and 3.18 Å apart from the ring centroid. Similar geometry of the anion–π interaction between s-triazine and chloride ion has been observed in a carousel copper(II)–triazine complex.[14] The torsion angles C2-N1-C7-C8 and N1-C7-C8-N9 of a flexible ethyleneammonium fragment are −106.7(2)° and 69.4(3)°, respectively. The Cl$^-$ ion is attached to the cation through a hydrogen bond to the NH_3^+ group (H91···Cl1 = 2.223(3) Å, N9···Cl1 = 3.149(2) Å, N9–H91···Cl1 = 164(2)°); it is surrounded by three other cations and joins to them by means of N–H···Cl$^-$, N$^+$–H···Cl$^-$, and C–H···Cl$^-$ interactions (Figure 3, top).

The dithione derivative **17** shows similar anion–π interactions to those observed in **15** (Figure 3, bottom). Again, the chloride anion connected to the ammonium group through the N9–H92···Cl1 hydrogen bond lies at a distance of 3.24 Å from the triazine ring plane and 3.28 Å from the ring centroid. The torsion angles C6-N1-C7-C8 and N1-C7-C8-N9 of ethyleneammonium fragment are 87.7(2)° and −65.1(2)°, respectively. The distance between the ring centroid and the chloride anion is 0.1 Å longer in the dithione **17** than in the monothione derivative **15**. This trend is in agreement with the theoretical results obtained for the chloride complexes of **TIA** and **DIA**. However, the experimentally observed difference is significantly larger than the calculated one (see Table 1). Interactions of anions with the dithiocyanurate ring were also observed in the bromide and iodide salts **18** and **19**, which are the analogues of the chloride salt **17** (Figure 4). In **18**, which is isostructural with **17**, the bromide anion connected to the ammonium group through the N9–H91···Br1 hydrogen bond lies at a distance of 3.33 Å from the triazine ring plane and 3.35 Å from the ring centroid. The conformation of the cation is almost identical in both structures (**17** and **18**) (C6-N1-C7-C8 and N1-C7-C8-N9 torsion angles are 87.6(2)° and −66.9(2)°, respectively). A further increase in the anion–ring-centroid distance is observed

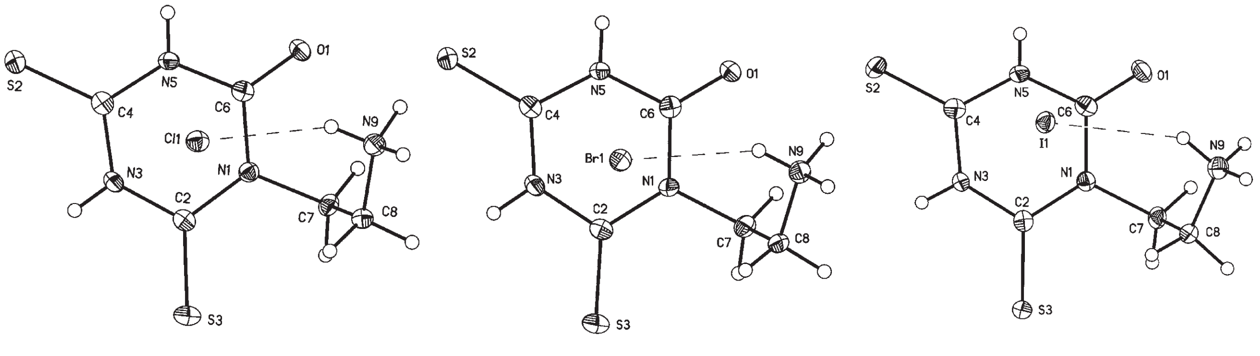


Figure 4. Ortep drawings of **17** (left), **18** (middle), and **19** (right) with atom labeling (thermal ellipsoids were drawn at 50% probability level).

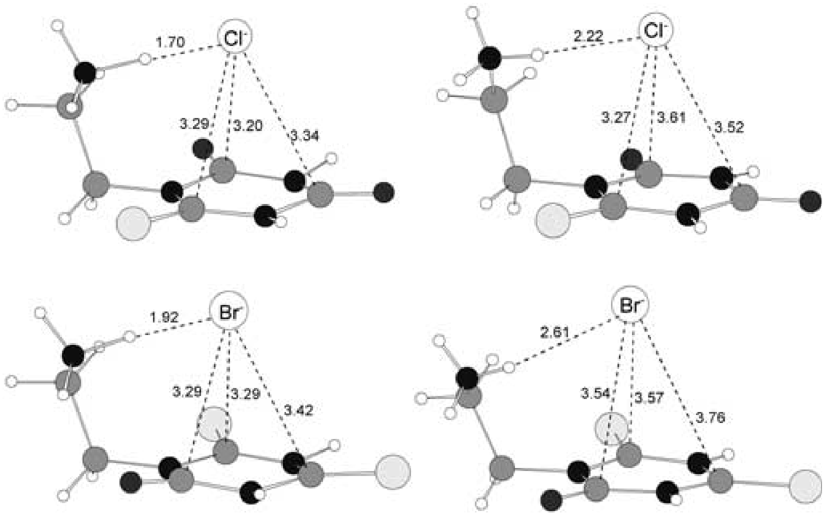


Figure 6. MP2(full)/6–31++G** optimized structures of **15** and **18** (left) and the corresponding experimental geometries obtained by X-ray crystallography (right). Distances are in Å.

in the salt **19**. The iodide ion, which is hydrogen bonded to the ammonium group, is 3.48 Å from the triazine ring plane and 3.51 Å from the ring centroid. The conformation of the cationic side arm is similar to that observed in the chloride and bromide salts (C6-N1-C7-C8 and N1-C7-C8-N9 torsion angles are 90.3(2)° and −74.8(2)°, respectively) (Figure 4). The observed lengthening of the anion–ring-centroid distances in **17**–**19** agrees well with the increase in the halide ion van der Waals radii.

The monothione derivative **16** (bromide salt) crystallizes as a hydrate and in contrast to the previously described salts no anion–π interactions are observed in this structure (see Figure 5). The conformation of the cation described by the torsion angles C2-N3-C7-C8 and N3-C7-C8-N9 of 90.8(3)° and 70.1(2)°, respectively, is not significantly different from that adopted by the cations exhibiting cooperative hydrogen bonding and anion–π interactions. However, the bromide ion hydrogen bonded to the NH_3^+ group is 4.51 Å from the nearest triazine ring centroid and at distance of 3.41 Å from the ring best plane. A likely explanation is that three relatively strong hydrogen bonds, in which the water molecule takes part in **16**, affect the mode of anion binding in the solid state.

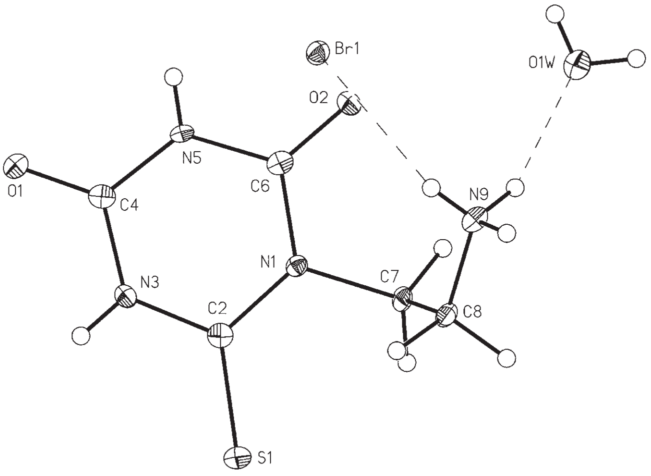


Figure 5. Crystal structure of **16**.

Finally, the information obtained by X-ray crystallography allows us to validate the level of calculation used in this work. We have optimized the compounds **15** and **18** at the MP2(full)/6–31++G** level of theory and compared the geometries with the experimental ones. The results are summarized in Figure 6. The geometry of the structures is similar (the anion is located over the ring), especially when you take into account that the optimized structures are fully relaxed in the gas phase, whereas the crystal structures are influenced by the packing forces. In general, the theoretical distances are shorter than the experimental ones and the planarity of the ring is lost to a greater extent at the theoretical level. This is probably due to the environment of the anion and the cation in the solid state, in which they participate in a variety of noncovalent interactions. The main difference observed between the experimental and theoretical results is the distance between the anion and the amonium group, which is in one case more than half of an angstrom. A likely explanation of the underestimation of the N−H···anion distance by the theoretical method is that in the solid state the anion is involved in three additional hydrogen bonds (see Figure 3), which are not taken into account in the theoretical model.

Conclusion

In summary, the results derived from theoretical calculations reveal that isocyanuric acids are suitable binding units to be used as binding blocks for the molecular recognition of anions. Moreover, they are synthetically more versatile than other electron-deficient aromatic rings, such as perfluorobenzene and nitrobenzenes. The substitution of oxygen atoms by sulfur atoms does not affect the binding ability of the ring due to a Q_{zz}/α compensating effect. The nature of the interaction derives from electrostatic and anion-induced polarization effects. The latter term increases as the number of sulfur atoms increases. In addition, we have synthesized and characterized several mono- and dithiocyanuric acid derivatives with an ethyleneammonium arm attached to one of

Table 3. Summary of crystal data and structure refinements for **15**–**19**.

	15	**16**	**17**	**18**	**19**
formula	$C_5H_9ClN_4O_2S$	$C_5H_{11}BrN_4O_3S$	$C_5H_9ClN_4OS_2$	$C_5H_9BrN_4OS_2$	$C_5H_9IN_4OS_2$
M_r	224.67	287.15	240.73	285.19	332.18
T [K]	296(2)	100(2)	170(2)	120(2)	130(2)
crystal system	monoclinic	triclinic	triclinic	triclinic	triclinic
space group	$P2_1/n$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$
a [Å]	7.4808(8)	6.6528(7)	6.8637(6)	7.0074(6)	5.9715(4)
b [Å]	10.7644(12)	8.4079(8)	8.2770(7)	8.3800(7)	7.3261(5)
c [Å]	11.7587(14)	10.3146(10)	9.8556(10)	9.9767(10)	12.9559(10)
α [°]	90.00	112.020(9)	87.370(7)	87.382(11)	74.708(6)
β [°]	98.523(9)	105.496(9)	71.679(8)	70.191(8)	76.954(6)
γ [°]	90.00	91.330(8)	68.372(8)	67.618(8)	82.277(6)
V [Å^3]	936.43(18)	510.49(10)	492.55(9)	507.32(9)	530.92(7)
Z	4	2	2	2	2
ρ_{calcd} [g cm^{-3}]	1.594	1.868	1.623	1.867	2.078
μ [mm^{-1}]	0.605	4.220	0.778	4.430	3.378
max/min transmission	–[a]	0.287/0.260	0.950/0.825	0.680/0.158	0.740/0.299
measured/independent reflns	4411/1634	4044/2081	5663/2011	5622/2078	5911/2162
R_{int}	0.0272	0.0321	0.0109	0.0148	0.0179
parameters refined	154	156	154	155	139
GOOF	1.075	1.045	1.070	1.063	1.091
R_1 [$I > 2\sigma(I)$]	0.0328	0.0237	0.0232	0.0190	0.0160
R_1 (all data)	0.0434	0.0253	0.0258	0.0209	0.0169
ρ_{max}/ρ_{min} [e Å^{-3}]	0.25/−0.29	0.534/−0.650	0.41/−0.34	0.36/−0.35	0.53/−0.43

[a] No absorption correction.

the triazine N atoms (**15**–**19**). X-ray crystallography showed that in their halide salts an anion–π interaction accompanied by a $N^+{-}H\cdots Cl^-$ hydrogen bond is a robust structural motif in the crystal structures.

Experimental Section

General: Melting points are not corrected. IR spectra were recorded on a FTIR Perkin–Elmer 1600 apparatus by using a mixture of the compound and KBr. ^{1}H and ^{13}C NMR spectra were taken at 500 and 125 MHz, respectively, with an acquisition time of 1.8 s. Chemical shifts were measured relative to the residual solvent signal at $\delta = 2.50$ or 7.26 ppm and $\delta = 39.5$ or 77 ppm, respectively.

Materials: All reagents were used directly as obtained commercially. 2-(Ethylthio)-7,8-dihydroimidazo[1,2-*a*]-1,3,5-triazine-4(6*H*)-thione (**13**) and 7,8-dihydroimidazo[1,2-*a*]-1,3,5-triazine-2,4(3*H*,6*H*)-dithione (**14**) were prepared according to a previous literature procedure.[34]

General procedure for the preparation of 2-(2,4-dioxo-6-thioxo-[1,3,5]triazinan-1-yl)ethylammonium chloride (15) and bromide (16), and 2-(2-oxo-4,6-dithioxo-[1,3,5]triazinan-1-yl)ethylammonium chloride (17), bromide (18), and iodide (19): A suspension of **13** or **14** (2.5 mmol) in 12% aqueous hydrochloric, hydrobromic, or hydroiodic acid (25–50 mL) was refluxed for 1–4 h. After cooling to ambient temperature prismatic colorless crystals of the product **15**–**19** suitable for X-ray analysis were obtained by slow evaporation.

2-(2,4-Dioxo-6-thioxo-[1,3,5]triazinan-1-yl)ethylammonium chloride (15): Yield 0.27 g (49%); m.p. 268–271 °C; ^{1}H NMR ([D$_6$]DMSO): $\delta = 3.10$–3.14 (m, 2H; CH$_2$), 4.39–4.41 (m, 2H; CH$_2$), 8.01 (s, 3H; NH), 11.99 (s, 1H; NH), 12.68 ppm (s, 1H; NH); IR: $\tilde{\nu} = 3254$, 3124, 2977, 2785, 1707, 1600, 1499, 1241, 1138, 1051 cm^{-1}; elemental analysis calcd (%) for $C_5H_9ClN_4O_2S$: C 26.73, H 4.04, N 24.94; found: C 26.12, H 4.02, N 24.79.

2-(2,4-Dioxo-6-thioxo-[1,3,5]triazinan-1-yl)ethylammonium bromide monohydrate (16): Yield 0.37 g (52%); m.p. 248–251 °C; ^{1}H NMR ([D$_6$]DMSO): $\delta = 3.11$–3.14 (m, 2H; CH$_2$), 4.36–4.41 (m, 2H; CH$_2$), 7.79 (s, 3H; NH), 12.01 (s, 1H; NH), 12.72 ppm (s, 1H; NH); IR: $\tilde{\nu} = 3586$, 3499, 3048, 1705, 1584, 1486, 1430, 1362, 1222, 1143, 1063 cm^{-1}; elemental analysis calcd (%) for $C_5H_{11}BrN_4O_3S$: C 20.91, H 3.86, N 19.51; found: C 21.03, H 3.93, N 19.75.

2-(2-Oxo-4,6-dithioxo-[1,3,5]triazinan-1-yl)ethylammonium chloride (17): Yield 0.29 (49%); m.p. 290 °C; ^{1}H NMR ([D$_6$]DMSO): $\delta = 3.04$–3.20 (m, 2H), 4,30–4.44 (t, $J = 5.5$ Hz 2H), 7.95 (br s, 3H; NH$^+$) 13.1 (br s, 1H; NH), 13.65 ppm (br s, 1H; NH); ^{13}C NMR ([D$_6$]DMSO): $\delta = 36.4$ 43.5, 146.0, 174.3, 176.3 ppm; elemental analysis calcd (%) for $C_5H_9ClN_4OS_2$: C 25.10, H 3.76, N 23.23; found: C 25.12, H 3.67, N 23.58.

2-(2-Oxo-4,6-dithioxo-[1,3,5]triazinan-1-yl)ethylammonium bromide (18): Yield 0.24 g (35%); m.p. 323–325 °C; IR: $\tilde{\nu} = 3117$, 2900, 2719, 1718, 1543, 1495, 1484, 1434, 1362, 1240, 1190, 1106, 950, 813, 736, 704 cm^{-1}; elemental analysis calcd (%) for $C_5H_9BrN_4OS_2$: C 21.20, H 3.17, N 19.61; found: C 21.47, H 3.02, N 19.51.

2-(2-Oxo-4,6-dithioxo-[1,3,5]triazinan-1-yl)ethylammonium iodide (19): Yield 0.59 g (72%); m.p. 294–297 °C; IR: $\tilde{\nu} = 3118$, 2979, 2854, 1715, 1542, 1455, 1430, 1357, 1240, 1188, 1119, 1096, 943, 868, 752 cm^{-1}; elemental analysis calcd (%) for $C_5H_9IN_4OS_2$: C 18.07, H 2.73, N 16.86; found: C 18.22, H 2.98, N 16.48.

Crystal structure determinations: The data were collected with a KM4CCD diffractometer with Mo$_{K\alpha}$ radiation ($\lambda = 0.71073$ Å). The structures were solved by direct methods (SHELXS-97[35]) and refined with SHELXL-97.[36] Summary of crystal data, data collection and structure refinement for **15**–**19** is given in Table 3. CCDC-274262–274266 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data request/cif.

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