10856 J. Phys. Chem. A **2008,** *112,* 10856–10863

Competition of Hydrogen Bonds and Halogen Bonds in Complexes of Hypohalous Acids with Nitrogenated Bases

Ibon Alkorta,*,[†] Fernando Blanco,[†] Mohammad Solimannejad,*,[‡] and Jose Elguero[†]

Instituto de Química Médica (CSIC), Juan de la Cierva, 3; 28006-Madrid, Spain, Quantum Chemistry Group, Department of Chemistry, Arak University, 38156-879 Arak, Iran, and Centre for Theoretical and Computational Chemistry, Department of Chemistry, University of Oslo, P.O. Box 1033, Blindern, N-0315 Oslo, Norway

Received: July 10, 2008; Revised Manuscript Received: August 29, 2008

A theoretical study of the complexes formed by hypohalous acids (HOX, X = F, Cl, Br, I, and At) with three nitrogenated bases (NH_3, N_2, and NCH) has been carried out by means of ab initio methods, up to MP2/aug-cc-pVTZ computational method. In general, two minima complexes are found, one with an OH···N hydrogen bond and the other one with a X···N halogen bond. While the first one is more stable for the smallest halogen derivatives, the two complexes present similar stabilities for the iodine case and the halogen-bonded structure is the most stable one for the hypoastatous acid complexes.

Introduction

Noncovalent interactions between molecules play a very important role in supramolecular chemistry, molecular biology, and material science. Among the various types of intermolecular interactions, the hydrogen bond is, without doubt, the most important one.[1−3] Although research has traditionally focused on the more common hydrogen-bonded interactions,[3−6] a growing body of experimental and theoretical evidence confirms that interactions such as -X···Y- (X = Cl, Br, or I; Y = N, O, S, or π) and even interactions such as -X···Y- (X = Cl, Br, or I; Y = Cl, Br, or I) also play a distinctive role in crystal engineering;[7−28] such interactions being called halogen bonds.

Halogen bonds are of particular interest in biochemistry and medicinal chemistry because they are often involved in protein−ligand interactions that are either biologically detrimental, as in the case of interactions involving organohalogens found in the environment, or beneficial, because of their potential usefulness in the design of novel ligands that interact with proteins in a very specific way.[29−35]

Like hydrogen-bonded complexes, halogen-bonded complexes were originally classified as charge-transfer complexes in which the charge transfer is considered to be the dominant factor in determining the complex structure. Today, we know, for both the hydrogen bond and the halogen bond, that consideration of only the charge-transfer interaction is insufficient to describe their ground-state stabilization and that the electrostatic effect, polarization, charge-transfer, and dispersion contributions all play important roles.[36]

Extensive studies have shown that many properties of the halogen bond are analogous to those of the hydrogen bond;[37−54] hence, existing explanations for hydrogen-bond phenomena can be applied to the behavior of the halogen bond, and vice versa.

The chemical properties of the hypohalous acids (HOX with X = F, Cl, Br, I, or At), which are powerful oxidizing agents, are of particular interest because they reflect the interplay between the σ-inductive role of the halogen atom in HOX and the repulsive interactions between the lone pairs of the adjacent oxygen and halogen atoms.[55] A number of studies have characterized the hydrogen bonded cluster formed by the hypohalous acids with themselves[56] or with other molecules.[57−60] Bearing in mind that the HOX species (where X is F, Cl, or Br) could be easily formed in the atmosphere (e.g., through reactions between the X and OH radicals), and that species including a halogen element are crucial for most of the ozone removal processes, the title complexes in the present study are of great interest in the field of atmospheric chemistry relevant to ecological aspects as well as in the crystal engineering field.

To the best of our knowledge, neither theoretical nor experimental data regarding the structural information of the interaction of nitrogenated bases with any of the hypohalous acids is available in the literature except for the effect of the presence of N_2 in the rotational spectra of hypochlorous acid.[61] In the absence of experimental information, a theoretical analysis of the existence of such complexes and their properties appears to be in order. The present work reports a detailed examination of the stabilities, electronic structure, and vibrational frequencies of these complexes.

Methods

The systems have been optimized at the MP2 computational level[62] with the 6-311++G(2d,2p)[63] and aug-cc-pVTZ[64] basis sets and a mixed basis set (from now on called "mix"), where def2-TZVPP[65] has been used for the halogen atoms and 6-311++G(2d,2p) for the rest of the atoms. Frequency calculations have been carried out for the first and third basis set considered, in order to confirm that the structures obtained correspond to energetic minima.

The use of ab initio supermolecule calculations is known to be susceptible to basis-set superposition error (BSSE) when finite basis sets are used. The most common way to correct BSSE is with the full counterpoise method.[66] Systematic studies at the restricted Hartree−Fock (RHF) level have indicated that the counterpoise-corrected interaction energies are no more reliable than the uncorrected ones.[67] At correlated levels,

---

* Authors to whom correspondence should be addressed: (I.A.) fax 34-91 564 48 53, e-mail ibon@iqm.csic.es; (M.S.) fax +98-861-2774031, e-mail m-solimannejad@araku.ac.ir or mohammad.solimannejad@kjemi.uio.no.

[†] Instituto de Química Médica (CSIC).

[‡] Arak University and University of Oslo.

10.1021/jp806101t CCC: $40.75

TABLE 1: Experimental and Calculated Geometries and Dipole Moments of Hypohalous Acids

source of data	H−O (Å)	O−X (Å)	H−O−X (deg)	dipole moment (D)
		HOF		
exp[94]	0.964	1.442	97.2	2.23[79,82,87]
MP2/mix	0.967	1.428	98.1	1.92
MP2/6-311++G(2d,2p)	0.967	1.436	97.8	1.95
MP2/aug-cc-pVTZ	0.967	1.436	97.8	1.88
		HOCl		
exp[95,96]	0.9643	1.6891	102.96	1.56
MP2/mix	0.965	1.696	102.3	1.57
MP2/6-311++G(2d,2p)	0.966	1.719	101.7	1.58
MP2/aug-cc-pVTZ	0.969	1.697	102.5	1.51
		HOBr		
exp[97]	0.9643	1.82793	103.05	1.38[80,83,85,89,92]
MP2/mix	0.966	1.832	102.4	1.49
MP2/6-311++G(2d,2p)	0.966	1.848	102.4	1.50
MP2/aug-cc-pVTZ	0.969	1.824	102.9	1.41
		HOI		
exp[98]	0.967(8)	1.9941(3)	103.89	[a]
MP2/mix	0.966	1.991	103.7	1.49
		HOAt		
MP2/mix	0.966	2.092	103.0	1.72

[a] No experimental data; calculated 1.40 (MP2)[86] and 1.44 (Lanl2DZ).[91]

application of the full counterpoise method caused a nonphysical increase in the dimension of virtual space.[68] Since the inclusion of a diffuse function has been shown to markedly reduce the BSSE effect,[69,70] the interaction energy of the clusters in this paper has been calculated as the difference between the supermolecule and the sum of the isolated monomers in their minimum configuration.

The electron density of the isolated molecules and complexes has been analyzed within the atoms in molecules (AIM) methodology[71] and the AIMPAC[72] and MORPHY98 programs.[73] The atomic properties have been obtained by integration within the atomic basins. Integration conditions have been modified until the integrated Laplacian value obtained for each atom is smaller, in absolute value, than 10^{-3}, since previous articles have shown that these conditions ensure a small error in the total energy and charge of the system.[74]

The natural bond orbital (NBO) method[75] has been used to analyze the interaction of occupied and empty orbitals with the NBO-5 program.[76] This kind of interactions are of main importance in the formation of hydrogen bonds and other charge-transfer complexes. In addition, natural steric analysis[77] has been used to characterize the repulsion of the electronic cloud of the monomers within the complex.

The absolute chemical shieldings have been evaluated within the GIAO approximation[78] at the MP2/6-311++G(2d,2p) computational level.

Results and Discussions

Hypohalous Acids. There has been great interest in the structure of hypohalous acids both experimentally and theoretically.[79−92] Only the radioactive hypoastatous acid (CAS 126331-89-3) although known,[93] has never been structurally studied or theoretically calculated.

Experimental gas-phase geometries are available for the four smaller hypohalous acids (X = F, Cl, Br, and I). The calculated geometries with the three computational methods here considered are in good agreement with the experimental ones (Table 1).

TABLE 2: Molecular Electrostatic Potential Minima

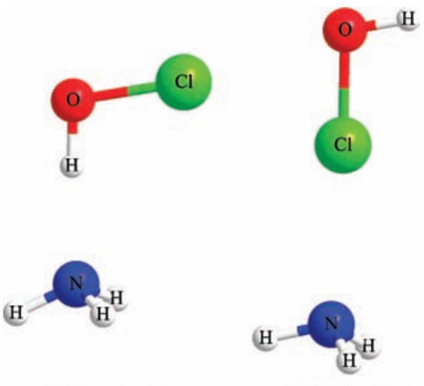
	MEP minimum (au)	
	oxygen	X atom
HOF	−0.0393	−0.0289
HOCl	−0.0442	−0.0163
HOBr	−0.0469	−0.0134
HOI	−0.0517	
HOAt	−0.0579	

As can be seen, the MP2/mix calculations reproduce fairly well the experimental dipole moments, both following approximately the Pauling electronegativity χ of X.[99] The largest discrepancy is found in the HOF molecule, in agreement with other reports that use correlated computational levels and large basis sets.[84,87], In contrast, small basis set at MP2 and RHF level provide a good estimate of the dipole moment of the HOF system.[82]

Two different types of minima have been found in the molecular electrostatic potential (MEP) for the three smaller members of the hypohalous acids (X = F, Cl, and Br): one associated with the oxygen lone pair and the other with the X atom (Table 2). However, the minima in the oxygen region are deeper than those in the X region. Only in the case of the fluorine derivatives can it be considered that both regions can compete for the interaction with electron-deficient moieties, as in dimer formation or complexation with other HB donors. For the larger derivatives with less electronegative halogens, HOI and HOAt, only the minima on the lone pair of the oxygen have been found.

The MEP minima on the oxygen became larger in absolute value as the size of the X atom increases. Linear correlations are found between the MEP minima and the value of the electronegativity of the X atom with square correlation coefficients of 0.94 and 0.999 for the values corresponding to the oxygen and X atom, respectively.

Complexes. Two different kinds of complexes between the five hypohalous acids and the three nitrogenated bases have been considered, one through a hydrogen bond (HB) interaction and the other through a halogen bond (XB) (Figure 1). For the fluorine derivative, only the HB complex is stable, while in the rest of the cases, both configurations are found to be local minima. The formation of HB and XB complexes occurs only with the assumption that the oxygen atom steals electronic charge from its two neighbors except in the HOF molecule, when the fluorine atom is more electronegative than the oxygen and thus only the HB complex is obtained.



$ClOH{:}NH_3$ (HB) $HOCl{:}NH_3$ (XB)

Figure 1. Optimized structure of the complexes between HOCl and NH_3 at the MP2/mix computational level.

TABLE 3: Interaction Energies[a]

	MP2/6-311++G(2d,2p)		MP2/aug-cc-pVTZ		MP2/mix	
	HB	XB	HB	XB	HB	XB
HOF−NH_3	−47.01		−47.25		−46.10	
HOCl−NH_3	−47.31	−21.05	−48.47	−19.93	−47.03	−18.57
HOBr−NH_3	−45.53	−33.16	−48.33	−35.57	−46.10	−31.10
HOI−NH_3					−45.08	−45.40
HOAt−NH_3					−41.94	−57.63
HOF−N_2	−10.14		−10.55		−9.81	
HOCl−N_2	−10.71	−6.08	−11.53	−6.14	−10.56	−5.60
HOBr−N_2	−10.49	−7.74	−12.14	−9.70	−10.60	−8.05
HOI−N_2					−10.80	−11.61
HOAt−N_2					−10.42	−15.69
HOF−NCH	−29.59		−30.11		−29.11	
HOCl−NCH	−29.45	−12.41	−30.68	−12.41	−29.25	−11.07
HOBr−NCH	−28.44	−18.30	−30.79	−21.22	−28.72	−17.74
HOI−NCH					−28.23	−26.97
HOAt−NCH					−26.38	−36.94

[a] All interaction energies are given in kilojoules per mole.

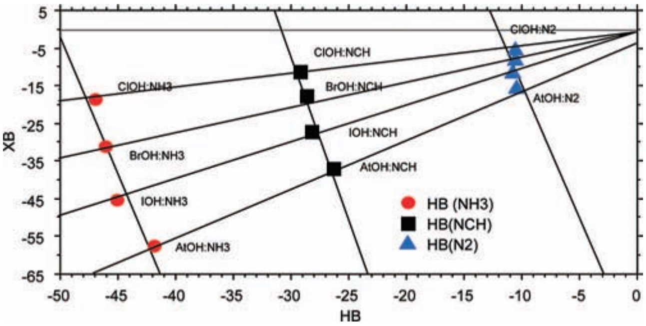


Figure 2. Halogen-bond vs hydrogen-bond interaction energies (in kilojoules per mole).

The energetic results (Table 3) show that, for any given case, the interaction values obtained with the three basis sets considered here are almost identical. These results corroborate the values obtained for those complexes resulting from the MP2/mix calculations.

We have analyzed the energetic values of Table 3 as a function of several independent variables. Since they are the most complete, we have selected as dependent variables the MP2/mix values (15 for HB and 12 for XB). We first note that these two series of values (those corresponding to FOH are missing) are not correlated (Figure 2). The HB energies are very much dependent on the nature of the base (NH_3, NCH, N_2) and not so much on the nature of the acid (although AtOH clearly produces weaker effects in the case of the stronger bases), while the XB energies depend on both. The lines connecting the effect of the acid (same color) have acceptable correlation coefficients for NH_3 (red, $R^2 = 0.983$) and NCH (black, $R^2 = 0.922$) but not for N_2 (blue, $R^2 = 0.06$, very small overall variation); on the other hand, those lines connecting the bases (three colors) have excellent correlation coefficients: ClOH, $R^2 = 0.989$; BrOH, $R^2 = 0.989$; IOH, $R^2 = 0.996$; AtOH, $R^2 = 1.000$. All these lines tend to the (0,0) point (no intercept) with slopes of 0.395, 0.662, 0.996, and 1.387, respectively. These values are correlated with Pauling's electronegativities ($R^2 = 0.990$) or electron affinities ($R^2 = 0.994$) of the halogens.

We have produced several multiple models using MP2/mix-calculated proton affinities and acidities of the monomers and other tabulated properties like Pauling's electronegativities, electron affinities, and polarizabilities. By use of normalized variables to avoid differences in the independent variables,[100,101] the HB energies depend on the proton affinity (PA) of the bases and on the electron affinities of X while the XB energies depend also (but less) on the PAs and much more on the electron affinities of X.

In order to evaluate the effect of halogen atoms in the HB complexes, the complexes of water with the three nitrogenated bases have been evaluated. The interaction energies obtained at the MP2/aug-cc-pVTZ computational level (−28.05, −18.39, and −6.58 kJ/mol for the complexes of H_2O with NH_3, NCH, and N_2, respectively) clearly indicate the strong withdrawing effect of the halogen atom of the hypohalous molecules that favors a stronger HB interaction.

The interatomic distances between the interacting atoms have been gathered in Table 4. For a given base, all the HB distances are very similar, increasing slightly from the Cl derivative to the At one, showing in general the complex with the hypofluorous acid has larger interatomic distances than the hypochlorous ones. Analogous complexes between H_2O and the nitrogenated bases present larger interatomic distances, in agreement with the energetic results discussed previously (1.957, 2.319, and 2.089 Å for H_2O-NH_3, H_2O-N_2, and H_2O-NCH, respectively, calculated at the MP2/aug-cc-pVTZ computational level). In the halogen-bonded cluster, the interatomic distances of the bromine derivatives are always shorter than the chlorine ones, and those of the astatine are larger than those of the hypoiodous acid.

In order to estimate the amount of overlap of the electronic cloud in the complexes studied in this paper, we have calculated for the isolated monomers the value of the radii in the direction of the interaction, along the symmetry axes in the nitrogenated bases and the OX and OH bonds in the hypohalous acids. For that purpose, a 0.001 e/au^3 electron density isosurface has been used (Table 5).[71] The values obtained are similar to those proposed by Pauling (1.5, 1.2, 1.35, 1.8, 1.95, and 2.15 Å for N, H, F, Cl, Br, and I, respectively).[102]

An interesting feature of these results is the increasing radii of the hydrogen atom of the hypohalous acids as the X atoms became larger, which corresponds to a decreasing value of electronegativity. Thus, the electron-withdrawing effect of the X atom is transmitted along two bonds, the OX and OH ones.

In all the cases considered, the sum of the quantities of Table 5 is much larger (between 0.64 and 1.54 Å) than the calculated intermolecular distance. As expected, the smaller differences are obtained in the weaker complexes, HB clusters with N_2 and weak XB complexes, and the larger in the stronger ones, those corresponding to complexes with NH_3.

TABLE 4: Interatomic Distances[a] of the Interacting Atoms

	MP2/6−311++G(2d,2p)		MP2/aug-cc-pVTZ		MP2/mix	
complexes	HB	XB	HB	XB	HB	XB
HOF−NH_3	1.791		1.773		1.799	
HOCl−NH_3	1.778	2.636	1.755	2.636	1.776	2.680
HOBr−NH_3	1.793	2.605	1.761	2.546	1.784	2.612
HOI−NH_3					1.794	2.663
HOAt−NH_3					1.826	2.678
HOF−N_2	2.174		2.152		2.163	
HOCl−N_2	2.168	3.077	2.145	3.009	2.167	3.070
HOBr−N_2	2.178	3.072	2.150	2.964	2.177	3.057
HOI−N_2					2.189	2.811
HOAt−N_2					2.217	2.992
HOF−NCH	1.934		1.918		1.943	
HOCl−NCH	1.924	2.862	1.902	2.818	1.926	2.867
HOBr−NCH	1.936	2.823	1.906	2.737	1.932	2.816
HOI−NCH					1.941	2.663
HOAt−NCH					1.965	2.749

[a] All interatomic distances are given in angstroms.

TABLE 5: Van der Waals Radii[a]

	N	
N_2	1.8492	
NH_3	2.0725	
NCH	1.9015	
	H	X
HOF	1.1614	1.5376
HOCl	1.1669	1.8577
HOBr	1.1706	1.9650
HOI	1.1788	2.1113
HOAt	1.1900	2.1434

[a] Calculated for the isolated monomers in the interaction direction by use of the 0.001 e/au^3 electron density isosurface calculated at the MP2/mix computational level. All radii are given in angstroms.

TABLE 6: Electron Density and Laplacian at Intermolecular Bond Critical Point[a]

	HB complexes		XB complexes	
	ρ	Lap	ρ	Lap
HOF−N_2	0.0146	0.0552		
HOF−NCH	0.0260	0.0841		
HOF−NH_3	0.0418	0.0922		
HOCl−N_2	0.0147	0.0554	0.0079	0.0360
HOCl−NCH	0.0272	0.0867	0.0131	0.0577
HOCl−NH_3	0.0443	0.0932	0.0235	0.0832
HOBr−N_2	0.0144	0.0544	0.0101	0.0414
HOBr−NCH	0.0269	0.0862	0.0178	0.0690
HOBr−NH_3	0.0435	0.0927	0.0320	0.0958
HOI−N_2	0.0141	0.0531	0.0122	0.0464
HOI−NCH	0.0264	0.0851	0.0226	0.0787
HOI−NH_3	0.0426	0.0922	0.0352	0.0921
HOAt−N_2	0.0133	0.0503	0.0159	0.0606
HOAt−NCH	0.0250	0.0820	0.0276	0.0975
HOAt−NH_3	0.0396	0.0899	0.0365	0.1020

[a] Calculated at the MP2/mix computational level.

Electron Density Analysis. The topological analysis of the electron density shows the presence of an intermolecular bond critical point (bcp) in all the complexes, HB as well as XB. In both cases, these bond critical points show small values of the electron density and positive Laplacian, an indication of the closed-shell characteristics of the interaction (Table 6). A similar conclusion can be reached by use of the electron localization function (ELF) of the complex, which resembles those of the isolated monomers and does not present any intermolecular basin.

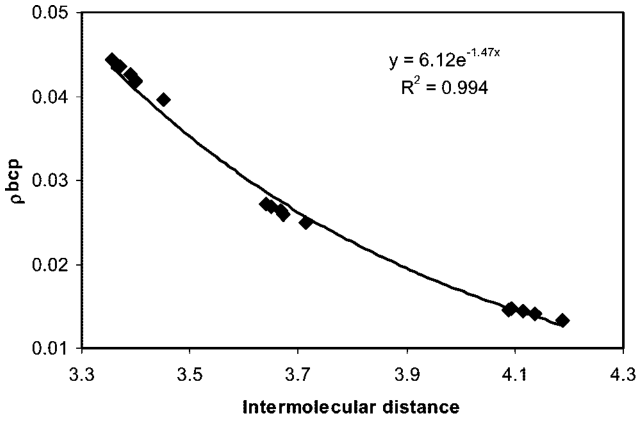


Figure 3. Electron density at bcp vs intermolecular distance (in atomic units) in HB complexes calculated at the MP2/mix computational level.

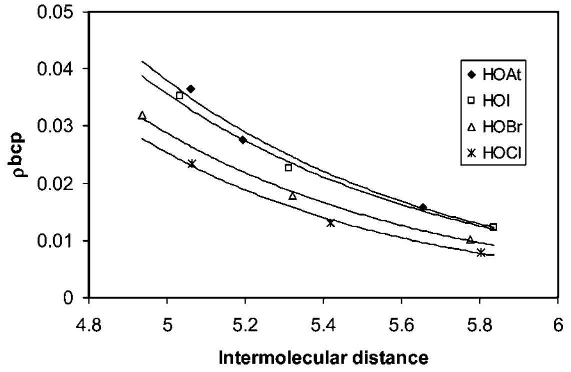


Figure 4. Electron density at bcp vs intermolecular distance (in atomic units) in XB complexes calculated at the MP2/mix computational level.

The electron density at the bcp and the bond distance in the HB complexes present an exponential relationship (Figure 3), similar to the one described by other HB complexes.[103−106] Analogous correlations are found in the XB complexes but are grouped on the basis of the interacting atoms (Figure 4). A comparison of the electron density at the bcp in HB and XB complexes shows that the most stable ones are the ones showing the largest values.

The integration of the properties within the atomic basins provides a tool to analyze the variation of the energy, charge, and volume associated with complex formation (Table 7). An

TABLE 7: Variation of the Properties[a] of Hypohalous Acids upon Complexation and Total Complex Volume[b]

	HB complexes				XB complexes			
	charge	ΔE	Δvol	Δvol total	charge	ΔE	Δvol	Δvol total
HOF−N_2	−0.011	5.08	−2.38	−9.27				
HOF−NCH	−0.027	7.72	−3.95	−15.68				
HOF−NH_3	−0.061	12.44	−4.29	−25.77				
HOCl−N_2	−0.010	−92.66	−2.16	−8.25	−0.002	−85.80	−0.71	−3.36
HOCl−NCH	−0.027	−74.32	−3.96	−15.69	−0.012	−68.33	−2.70	−9.81
HOCl−NH_3	−0.064	−40.40	−4.08	−25.99	−0.054	−34.03	−3.15	−21.42
HOBr−N_2	−0.008	−48.60	−3.09	−8.90	−0.002	−42.16	−2.71	−6.91
HOBr−NCH	−0.026	−32.42	−4.63	−16.14	−0.017	−28.14	−4.94	−15.82
HOBr−NH_3	−0.063	−13.52	−4.94	−26.43	−0.080	−23.29	−6.66	−31.35
HOI−N_2	−0.007	*c*	−2.81	−8.10	0.000	*c*	−5.80	−11.49
HOI−NCH	−0.024	*c*	−3.86	−15.03	−0.018	*c*	−8.77	−22.89
HOI−NH_3	−0.061	*c*	−3.36	−24.32	−0.085	*c*	−7.41	−34.71
HOAt−N_2	−0.005	*c*	−2.87	−7.59	0.002	*c*	−8.75	−16.74
HOAt−NCH	−0.021	*c*	−3.48	−13.84	−0.018	*c*	−10.70	−27.50
HOAt−NH_3	−0.055	*c*	−3.09	−22.69	−0.085	*c*	−7.04	−35.40

[a] Charge (in electron units), energy (in kilojoules per mole), and volume (in atomic units) are compared. [b] Obtained by use of the AIM methodology at the MP2/mix computational level. [c] In these cases, unreliable results are obtained due to the used of ECP basis set in the halogen atoms.

TABLE 8: Main Component of the Intermolecular Orbital Interaction and Distortion Energy[a] of the Monomers upon Complex Formation

	HB complexes		XB complexes	
complex	Lp (N) → σ^* (HO)	monomer distortion	Lp (N) → σ^* (XO)	monomer distortion
HOF−NH_3	130.6	1.35		
HOCl−NH_3	137.7	1.79	41.3	0.47
HOBr−NH_3	130.5	1.76	82.8	1.07
HOI−NH_3	120.4	1.84	112.3	1.20
HOAt−NH_3	103.6	1.43	135.8	1.25
HOF−N2	13.4	0.01		
HOCl−N2	11.9	0.03	5.3	0.00
HOBr−N2	10.5	0.04	10.2	0.00
HOI−N2	8.9	0.04	17.7	0.01
HOAt−N2	7.0	0.04	33.4	0.02
HOF−NCH	45.0	0.19		
HOCl−NCH	46.4	0.28	11.2	0.06
HOBr−NCH	43.3	0.30	25.0	0.12
HOI−NCH	39.0	0.34	44.3	0.21
HOAt−NCH	32.8	0.30	75.0	0.31

[a] All components and distortion energies are given in kilojoules per mole.

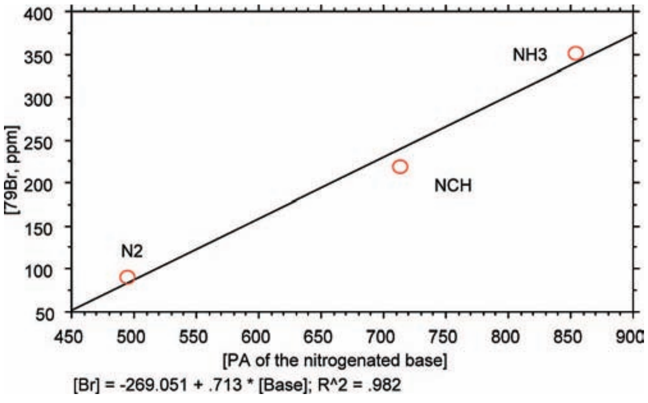


Figure 5. Plot of the effect produced on the ^{79}Br signal of BrOH hydrogen-bonded to three bases.

energy stabilization of the hypohalous acid is observed upon complexation with the exception of the HB complexes of HOF, where there is a loss in energy. Counterintuitively, the larger stabilization occurs in the N_2 complexes and the smaller in the NH_3. The integrated values of the energy, in those cases where effective core potential basis sets have been used, have not been considered since they provide nonphysical results.

In general, a charge transfer is observed from the nitrogenated bases to the hypohalous acids. The amount of this transfer is clearly dependent on the strength of the interaction; thus, in all cases, the largest transfer is observed for the NH_3 complexes, followed by the NCH ones, and the smallest in the N_2 cases.

A molecular volume contraction is observed in both hypohalous acids and nitrogenated bases upon complexation. In general, the extent of the volume contraction is dependent on the strength of the interaction, which is associated with closer proximity of the interacting molecules and is more important in the nitrogenated bases than in the hypohalous acids. A comparison of the HB and XB complexes of iodine and astatine derivatives shows that the latter presents a more important contraction, which is an indication that, in compressed media, this kind of complex should present an additional stabilization versus the former.

Natural Bond Orbital Analysis. HB complex formation is associated with an orbital interaction between the lone pair of the electron donor and the antibonding HX orbital.[107] A similar interaction has been found for the XB complexes (Table 8). In the HB complexes the energetic values of the orbital interaction can be clustered on the basis of nitrogenated bases, with the values decreasing as the size of the halogen atom increases, which is similar to the tendency observed for the interaction energy. In the case of the XB complexes, the orbital interaction increases dramatically with the size of the halogen atom, again in agreement with the tendencies observed for the interaction energy.

In any case, the orbital interaction energy obtained for most of the complexes considered here is larger than the corresponding interaction energy. Among the different sources that can explain these differences, we have assesed the value of the distortion energy of the monomers upon complex formation. However, the values of the distortion energy are very small when compared to the interaction energy.

Steric repulsion of the monomers within the complexes has been evaluated by natural steric analysis, and it has been found that, for the stronger HB complexes, those with NH_3, it ranges between 50 and 78 kJ/mol. When the orbital interaction energy and the steric repulsion are added, values close to those of Table

TABLE 9: Variation of Chemical Shieldings from Monomers to Dimers[a]

	hydrogen-bonded complexes			halogen-bonded complexes	
	$FOH-NH_3$	$ClOH-NH_3$	$BrOH-NH_3$	$HOCl-NH_3$	$HOBr-NH_3$
N	−6.85	−6.11	−5.66	−7.16	−9.12
H	−1.04	−1.11	−1.05	−0.06	−0.27
H	−0.73	−0.54	−0.49	−0.03	−0.25
H	−0.73	−0.54	−0.49	−0.03	−0.25
H	−5.97	−6.57	−6.54	−0.23	−0.70
X	50.32	134.67	351.73	59.61	400.63
O	−55.21	−31.82	−34.14	−45.62	−82.81
	FOH−NCH	ClOH−NCH	BrOH−NCH	HOCl−NCH	HOBr−NCH
N	15.88	16.04	15.47	5.39	9.60
C	1.05	1.04	1.00	0.76	0.82
H	−0.28	−0.25	−0.24	0.08	0.03
H	−2.15	−2.31	−2.34	0.08	−0.19
X	29.78	82.29	219.27	−13.66	104.22
O	−25.58	−13.18	−14.84	−13.16	−33.24
	$FOH-N_2$	$ClOH-N_2$	$BrOH-N_2$	$HOCl-N_2$	$HOBr-N_2$
N1	7.53	7.32	7.06	2.44	4.16
N2	−0.81	−0.96	−0.94	0.05	−0.41
H	−0.36	−0.28	−0.30	−0.04	−0.18
X	11.24	36.02	90.84	−0.40	61.63
O	−9.72	−5.79	−6.90	−7.32	−17.00

[a] Calculated at the MP2/6-311++G(2d,2p) computational level. All chemical shieldings are given in parts per million (ppm). Atoms of the hypohalous acids are shown in italic type.

3 are obtained for the NH_3 complex, but for the remaining cases this analysis is not so satisfactory.

NMR Absolute Shieldings. With regard to the isolated monomers (see Supporting Information), formation of the complexes leads to the values presented in Table 9. HB complex formation shift the signal of the hydrogen atom involved to a lower field up to 6.6 ppm in the $ClOH-NH_3$ complex. In the XB complexes, the variation observed in the interacting halogen atom depends on its nature; thus, the chlorine atom shifted at higher fields while the opposite happens to the bromine one. Something similar happens in the shielding of the nitrogen atom involved in the interaction since positive variations are obtained in the NCH and N_2 complexes and negative in the NH_3 ones.

The different values obtained for the HB complexes are highly correlated, both in what concerns the acid and in what concerns the base:

$$\sigma\mathrm{ClOH} = (0.989 \pm 0.016)\sigma\mathrm{FOH} \qquad n = 8, r^2 = 0.998 \quad (1)$$

$$\sigma\mathrm{BrOH} = (0.949 \pm 0.019)\sigma\mathrm{FOH} \qquad n = 8, r^2 = 0.997 \quad (2)$$

$$\sigma\mathrm{N}_2 = (0.416 \pm 0.003)\sigma\mathrm{NCH} \qquad n = 9, r^2 = 0.999 \quad (3)$$

$$\sigma\mathrm{NH}_3 = (1.621 \pm 0.031)\sigma\mathrm{NCH} \qquad n = 9, r^2 = 0.997 \quad (4)$$

The slopes for the acids are much closer to unity than those of the bases, but the acids are much more alike ($\Delta G° = 1490$ kJ mol^{-1} for FH, 1461 kJ mol^{-1} for ClOH, and 1452 kJ mol^{-1} for BrOH) than the bases (PA = 712.9 kJ mol^{-1} for NCH, 493.8 kJ mol^{-1} for N_2, and 853.6 kJ mol^{-1} for NH_3).[108] Actually, the effects are proportional to the basicity, with correlation coefficients of 0.9 or greater (see an example in Figure 5).

Concerning the halogen-bonded complexes, the correlations are much poorer; for instance, between BrOH and ClOH, R^2 amounts only to 0.79. The effects are also dependent on the proton affinities of the bases, but the quality of the correlation is lower although the sign and the values of the slopes are similar. However, in the first case, the atoms are separated by three bonds (a ^{3}H bond) and in the second one by a halogen bond (a ^{1}X bond).[109]

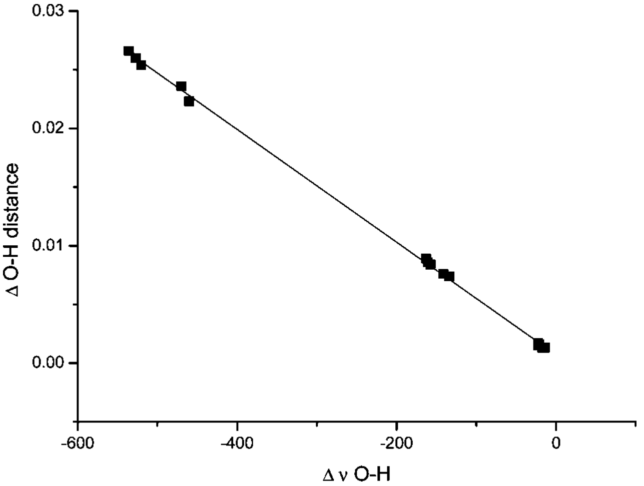


Figure 6. Variation of OH distance vs variation of bond stretching in HB complexes calculated at the MP2/mix level. The linear correlation presents an adjusted square correlation coefficient of 0.9994.

Stretching Frequencies. Complex formation produces a red shift of the OH stretching in the HB clusters and of the OX stretching in the XB ones. In both cases, linear relationships can be found between the bond distances or their variation and the bond stretching (Figures 6 and 7).

In addition, HB formation produces a small shortening of the OX bond and a small blue shift of the corresponding frequency, except for the HOF derivatives, where the opposite happens. Something similar occurs in the XB complexes with the OH bonds; the blue shift in these systems is between 1 and 28 cm^{-1}.

Conclusions

A theoretical study of the hydrogen-bonded and halogen-bonded complexes formed by the hypohalous acids with three

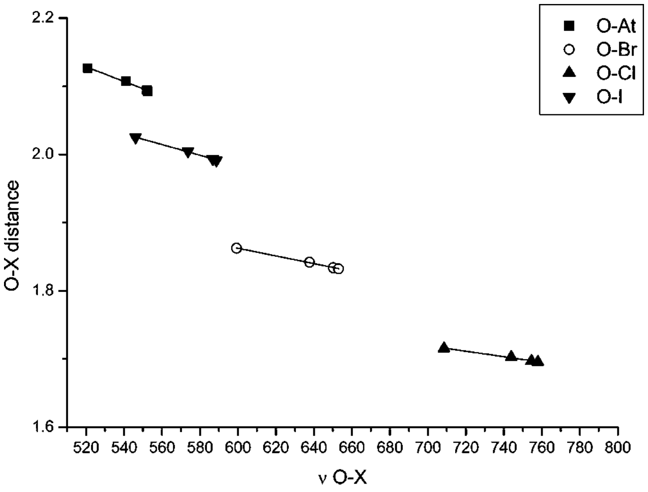


Figure 7. O−X distance vs bond stretching for each family of compounds in the XB complexes calculated at the MP2/mix level. The linear correlation presents the following adjusted square correlation coefficients: 0.988, 0.996, 0.989, and 0.995 for the At, Br, Cl, and I derivatives, respectively.

nitrogenated bases has been carried out by means of ab initio MP2 computational methods. The energetic results show that the HB complexes are favored in the smaller hypohalous acid derivatives (X = F, Cl, and Br) while the complexes of the hypoiodous acid present similar stability, and for the hypoastatous acid, the HX complex is more stable than the HB one. The interaction energies of the HB complexes have been correlated with the PA of the bases and with the electron affinities of X atom, while the XB energies depend mainly on the electron affinities of X.

Analysis of the electron density of the complexes shows an exponential relationship between electron density at the bcp and the interatomic distance of the atoms involved in the interaction. On the basis of the NBO analysis, the orbital interaction between the electrons of the bases and the corresponding antibonding interacting orbital of the HOX molecules is one of the most important sources of stabilization.

The calculated chemical shielding shows important variation upon complex formation. The bond stretching variations are linearly dependent with the bond variation observed in both HB and XB complexes.

Acknowledgment. We acknowledge financial support from the Spanish Ministerio de Educación y Ciencia (Project CTQ2007-61901/BQU) and the Comunidad Autónoma de Madrid (Project MADRISOLAR, ref S-0505/PPQ/0225). Thanks are given to CTI (CSIC) for allocation of computer time.

Supporting Information Available: Cartesian coordinates of the optimized complexes at the MP2 level using the def2-TZVPP basis set for the halogen atoms and the 6-311++G(2d,2p) one for the rest and absolute chemical shieldings of the isolated monomers. This information is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Jeffrey, G. A. *An Introduction to Hydrogen Bonding*; Oxford University Press: New York, 1997.

(2) Scheiner, S. *Hydrogen Bonding*; Oxford University Press: New York, 1997.

(3) Desiraju, G. R.; Steiner, T. *The Weak Hydrogen Bond*; Oxford University Press: Oxford, U.K., 1999.

(4) Nishio, M.; Hirota, M.; Umezawa, Y. *The CH Interaction*; Wiley−VCH: New York, 1998.

(5) *Molecular Interactions: From Van der Waals to Strong Bound Complexes*; Scheiner, S., Ed.; Wiley: Chichester, U.K., 1997.

(6) Jeffrey, J. A.; Saenger, W. *Hydrogen Bonding in Biological Structures*; Springer-Verlag: Berlin, 1991.

(7) Umeyama, H.; Morokuma, K.; Yamabe, S. *J. Am. Chem. Soc.* **1977**, *99*, 330.

(8) Kollman, P.; Dearling, A.; Kochanski, E. *J. Phys. Chem.* **1982**, *86*, 1607.

(9) Røeggen, I.; Dahl, T. *J. Am. Chem. Soc.* **1992**, *114*, 511.

(10) Price, S. L.; Stone, A. J.; Lucas, J.; Rowland, R. S.; Thornley, A. E. *J. Am. Chem. Soc.* **1994**, *116*, 4910.

(11) (a) Legon, A. C.; Lister, D. G.; Thorn, J. C. *J. Chem. Soc., Chem. Commun.* **1994**, 757. (b) Legon, A. C.; Lister, D. G.; Thorn, J. C. *J. Chem. Soc., Faraday Trans.* **1994**, *90*, 3205. (c) Bloemink, H. I.; Legon, A. C.; Thorn, J. C. *J. Chem. Soc., Faraday Trans.* **1994**, *90*, 781. (d) Legon, A. C. *J. Chem. Soc., Faraday Trans.* **1995**, *91*, 781. (e) Legon, A. C. *Chem.—Eur. J.* **1998**, *4*, 1890.

(12) Desiraju, G. R. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2311.

(13) Latajka, Z.; Berski, S. *THEOCHEM* **1996**, *371*, 11.

(14) Ruiz, E.; Salahub, D. R.; Vela, A. *J. Phys. Chem.* **1996**, *100*, 12265.

(15) Lommerse, J. P. M.; Stone, A. J.; Taylor, R.; Allen, F. H. *J. Am. Chem. Soc.* **1996**, *118*, 3108.

(16) Bürger, H. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 718.

(17) Zhang, Y.; Zhao, C.-Y.; You, X.-Z. *J. Phys. Chem. A* **1997**, *101*, 2879.

(18) Alkorta, I.; Rozas, I.; Elguero, J. *J. Phys. Chem. A* **1998**, *102*, 9278.

(19) Amico, V.; Meille, S. V.; Corradi, E.; Messina, M. T.; Resnati, G. *J. Am. Chem. Soc.* **1998**, *120*, 8261.

(20) Farina, A.; Meille, S. V.; Messina, M. T.; Metrangolo, P.; Resnati, G.; Vecchio, G. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 2433.

(21) Corradi, E.; Meille, S. V.; Messina, M. T.; Metrangolo, P.; Resnati, G. *Angew. Chem., Int. Ed.* **2000**, *39*, 1782.

(22) Valerio, G.; Raos, G.; Meille, S. V.; Metrangolo, P.; Resnati, G. *J. Phys. Chem. A* **2000**, *104*, 1617.

(23) Karpfen, A. *J. Phys. Chem. A* **2000**, *104*, 6871.

(24) Walsh, R. B.; Clifford, W.; Padgett, C. W.; Metrangolo, P.; Resnati, G.; Hanks, T. W.; Pennington, W. T. *Cryst. Growth Des.* **2001**, *1*, 165.

(25) Metrangolo, P.; Resnati, G. *Chem.—Eur. J.* **2001**, *7*, 2511.

(26) Romaniello, P.; Francesco Lelj, F. *J. Phys. Chem. A* **2002**, *106*, 9114.

(27) Nangia, A. *Cryst. Eng. Commun.* **2002**, *17*, 1.

(28) Burton, D. D.; Fontana, F.; Metrangolo, P.; Pilatid, T.; Resnatic, G. *Tetrahedron Lett.* **2003**, *44*, 645.

(29) Auffinger, P.; Hays, F. A.; Westhof, E.; Ho, P. S. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101* (48), 16789.

(30) Battistutta, R.; Mazzorana, M.; Sarno, S.; Kazimierczuk, Z.; Zanotti, G.; Pinna, L. A. *Chem. Biol.* **2005**, *12*, 1211.

(31) Ghosh, M.; Meerts, I. A. T. M.; Cook, A.; Bergman, A.; Brouwer, A.; Johnson, L. N. *Acta Crystallogr., Sect. D: Biol. Crystallogr.* **2000**, *56*, 1085.

(32) Himmel, D. M.; Das, K.; Clark, A. D.; Hughes, S. H.; Benjahad, A.; Oumouch, S.; Guillemont, J.; Coupa, S.; Poncelet, A.; Csoka, I.; Meyer, C.; Ries, K.; Nguyen, C. H.; Grierson, D. S.; Arnold, E. *J. Med. Chem.* **2005**, *48*, 7582.

(33) Jiang, Y.; Alcaraz, A. A.; Chen, J. M.; Kobayashi, H.; Lu, Y. J.; Snyder, J. P. *J. Med. Chem.* **2006**, *49*, 1891.

(34) López-Rodriguez, M. L.; Murcia, M.; Benhamu, B.; Viso, A.; Campillo, M.; Pardo, L. *J. Med. Chem.* **2002**, *45*, 4806.

(35) Metrangolo, P.; Neukirch, H.; Pilati, T.; Resnati, G. *Acc. Chem. Res.* **2005**, *38*, 386.

(36) Lommerse, J. P. M.; Stone, A. J.; Taylor, R.; Allen, F. H. *J. Am. Chem. Soc.* **1996**, *118*, 3108.

(37) Metrangolo, P.; Resnati, G. *Chem.—Eur. J.* **2001**, *7*, 2511, and references therein.

(38) Metrangolo, P.; Neukirch, H.; Pilati, T.; Resnati, G. *Acc. Chem. Res.* **2005**, *38*, 386, and references therein.

(39) Metrangolo, P.; Resnati, G.; Pilati, T.; Liantonio, R.; Meyer, F. *J. Polym. Sci., Part A: Polym. Chem.* **2007**, *45*, 1, and references therein.

(40) Auffinger, P.; Hays, F. A.; Westhof, E.; Ho, P. S. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 16789.

(41) Metrangolo, P.; Pilati, T.; Resnati, G. *Cryst. Eng. Commun.* **2006**, *8*, 946.

(42) Wang, W. Z.; Wong, N. B.; Zheng, W. X.; Tian, A. M. *J. Phys. Chem. A* **2004**, *108*, 1799.

(43) Zou, J. W.; Jiang, Y. J.; Guo, M.; Hu, G. X.; Zhang, B.; Liu, H. C.; Yu, Q. S. *Chem.—Eur. J.* **2005**, *11*, 740.

(44) Wang, W. Z.; Tian, A. M.; Wong, N. B. *J. Phys. Chem. A* **2005**, *109*, 8035.

(45) Riley, K. E.; Merz, K. M. *J. Phys. Chem. A* **2007**, *111*, 1688.

(46) Lu, Y. X.; Zou, J. W.; Wang, Y. H.; Jiang, Y. J.; Yu, Q. S. *J. Phys. Chem. A* **2007**, *111*, 10781.

(47) Valerio, G.; Raos, G.; Meille, S. V.; Metrangolo, P.; Resnati, G. *J. Phys. Chem. A* **2000**, *104*, 1617.

(48) Farina, A.; Meille, S. V.; Messina, M. T.; Metrangolo, P.; Resnati, G.; Vecchio, G. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 2433.

(49) Liantonio, R.; Luzzati, S.; Metrangolo, P.; Pilati, T.; Resnati, G. *Tetrahedron* **2002**, *58*, 4023.

(50) Fox, D. B.; Liantonio, R.; Metrangolo, P.; Pilati, T.; Resnati, G. *J. Fluorine Chem.* **2004**, *125*, 271.

(51) Politzer, P.; Lane, P.; Concha, M. C.; Ma, Y.; Murria, J. S. *J. Mol. Model.* **2007**, *13*, 305.

(52) Metrangolo, P.; Resnati, G.; Pilati, T.; Biella, S. Halogen Bonding in Crystal Engineering. In *Halogen Bonding: Fundamentals and Applications*; Metrangolo, P., Resnati, G., Eds.; Springer: Berlin/Heidelberg, 2008; pp 105−136.

(53) Grabowski, S. J.; Bilewicz, E. *Chem. Phys. Lett.* **2006**, *427*, 51.

(54) Palusiak, M.; Grabowski, S. J. *Struct. Chem.* **2008**, *19*, 5.

(55) Appelman, E. H. *Acc. Chem. Res.* **1973**, *6*, 113.

(56) Solimannejad, M.; Alkorta, I.; Elguero, J. *Chem. Phys. Lett.* **2008**, *454*, 201.

(57) Solimannejad, M.; Ljupco Pejov, L. *J. Phys. Chem. A* **2005**, *109*, 825.

(58) Solimannejad, M.; Alkorta, I.; Elguero, J. *Chem. Phys. Lett.* **2007**, *449*, 23.

(59) Solimannejad, M.; Scheiner, S. *J. Phys. Chem. A* **2008**, *112*, 4120.

(60) Jalbout, A.; Li, X.; Solimannejad, M. *Chem. Phys. Lett.* **2006**, *420*, 204.

(61) Drouin, E. J. *J. Quant. Spectrosc. Radiat. Transf.* **2007**, *103*, 558.

(62) Møller, C.; Plesset, M. S. *Phys. Rev.* **1934**, *46*, 618.

(63) Frisch, M. J.; Pople, J. A.; Binkley, J. S. *J. Chem. Phys.* **1984**, *80*, 3265.

(64) Dunning, T. H. *J. Chem. Phys.* **1989**, *90*, 1007.

(65) Weigend, F.; Ahlrichs, R. *Phys. Chem. Chem. Phys.* **2005**, *7*, 3297.

(66) Boys, S. F.; Bernardi, F. *Mol. Phys.* **1970**, *19*, 553.

(67) Schwenke, D. W.; Truhlar, D. G. *J. Chem. Phys.* **1985**, *82*, 2418.

(68) Cook, D. B.; Sordo, J. A.; Sordo, T. L. *Int. J. Quantum Chem.* **1993**, *48*, 375.

(69) Frisch, M. J.; Del Bene, J. E.; Binkley, J. S.; Schaefer, H. F., III *J. Chem. Phys.* **1986**, *84*, 2279.

(70) King, B. F.; Weinhold, F. *J. Chem. Phys.* **1995**, *103*, 333.

(71) Bader, R. F. W. *Atoms in Molecules: A Quantum Theory*; Clarendon Press: Oxford, U.K., 1990.

(72) Biegler-König, F. W.; Bader, R. F. W.; Tang, T. H. *J. Comput. Chem.* **1982**, *3*, 317.

(73) Popelier, P. L. A., with a contribution from Bone, R. G. A. (UMIST, England, EU) MORPHY98, a topological analysis program; 0.2 ed., 1999.

(74) Alkorta, I.; Picazo, O. *Arkivoc* **2005**, *ix*, 305.

(75) Reed, A. E.; Curtiss, L. A.; Weinhold, F. *Chem. Rev* **1988**, *88*, 899.

(76) Glendening, E. D.; Badenhoop, K.; Reed, A. E.; Carpenter, J. E.; Bohmann, J. A.; Morales, C. M.; Weinhold, F. *NBO 5.0*; Theoretical Chemistry Institute: University of Wisconsin, Madison, WI, 2001.

(77) Badenhoop, J. K.; Weinhold, F. *J. Chem. Phys.* **1997**, *107*, 5406.

(78) London, F. *J. Phys. Radiat.* **1937**, *8*, 397.

(79) Thiel, W.; Scuseria, G.; Schaeffer, H. F., III; Allen, W. D. *J. Chem. Phys.* **1988**, *89*, 4965.

(80) Koga, Y.; Takeo, H.; Kondo, S.; Sugie, M.; Matsumura, C.; McRae, G. A.; Cohen, E. A. *J. Mol. Spectrosc.* **1989**, *138*, 467.

(81) Lee, T. J. *J. Phys. Chem.* **1994**, *98*, 3697.

(82) Burk, P.; Koppel, I. A.; Rummel, A.; Trummal, A. *J. Phys. Chem.* **1995**, *99*, 1432.

(83) Palmieri, P.; Puzzarini, C.; Tarroni, R. *Chem. Phys. Lett.* **1996**, *256*, 409.

(84) Lee, T. J.; Rice, J. E.; Dateo, C. E. *Mol. Phys.* **1996**, *89*, 1359.

(85) Peterson, K. A. *Spectrochim. Acta, Part A* **1997**, *53A*, 1051.

(86) Breidung, J.; Thiel, W.; Gauss, J.; Stanton, J. F. *J. Chem. Phys.* **1999**, *110*, 3687.

(87) Berski, S.; Silvi, B.; Latajka, Z.; Leszczynski, J. *J. Chem. Phys.* **1999**, *111*, 2542.

(88) Muenter, J. S.; Rebstein, J.; Callegari, A.; Rizzo, T. R. *J. Chem. Phys.* **1999**, *111*, 3488.

(89) Peterson, K. A. *J. Chem. Phys.* **2000**, *113*, 4598.

(90) Vander Auwera, J.; Kleffmann, J.; Flaud, J.-M.; Pawelke, G.; Bürger, H.; Hurtmans, D.; Pétrisse, R. *J. Mol. Spectrosc.* **2000**, *204*, 36.

(91) Begovic, N.; Markovic, Z.; Anic, S.; Kolar-Anic, L. *J. Phys. Chem.* **2004**, *108*, 651.

(92) Orphal, J.; Flaud, J.-M.; Kou, Q.; Kwabia Tchana, F.; Pirali, O. *J. Mol. Struct.* **2005**, *742*, 153.

(93) Greenwood, N. N.; Earnshaw, A. *Chemistry of Elements*, 2nd ed.; Elsevier: Amsterdam, 1997; p 886.

(94) Kim, H.; Pearson, E. F.; Appelman, E. H. *J. Chem. Phys.* **1972**, *56*, 1.

(95) Deeley, C. M. *J. Mol. Spectrosc.* **1987**, *122*, 481.

(96) Callegari, A.; Theulé, P.; Schmied, R.; Rizzo, T. R.; Muenter, J. S. *J. Mol. Spectrosc.* **2003**, *221*, 116.

(97) Cohen, E. A.; McRae, G. A.; Tan, T. L.; Friedl, R. R.; Johns, J. W. C.; Noel, M. *J. Mol. Spectrosc.* **1995**, *173*, 55.

(98) Ozeki, H.; Saito, S. *J. Chem. Phys.* **2004**, *120*, 5110.

(99) Lide, D. R. *CRC Handbook of Chemistry and Physics*, 84th ed.; CRC Press: Boca Raton, FL, 2004.

(100) Carlson, R. *Design and optimization in organic synthesis*; Elsevier: Amsterdam, 1992; p 51.

(101) Khuri, A. I.; Cornell, J. A. *Response Surfaces*; Marcel Dekker: New York, 1987; p 46.

(102) Pauling, L. *The Nature of the Chemical Bond*, 3rd ed.; Cornell University Press: Ithaca, NY, 1960.

(103) Alkorta, I.; Rozas, I.; Elguero, J. *Struct. Chem.* **1998**, *9*, 243.

(104) Alkorta, I.; Barrios, L.; Rozas, I.; Elguero, J. *THEOCHEM* **2000**, *496*, 131.

(105) Knop, O.; Rankin, K. N.; Boyd, R. J. *J. Phys. Chem. A* **2001**, *105*, 6552.

(106) Espinosa, E.; Alkorta, I.; Elguero, J.; Molins, E. *J. Chem. Phys.* **2002**, *117*, 5529.

(107) Weinhold, F.; Landis, C. *Valency and bonding*; Cambridge University Press: Cambridge, U.K., 2005.

(108) NIST Chemistry Webbook. http://webbook.nist.gov/chemistry/, June 2005 release.

(109) Del Bene, J. E.; Alkorta, I.; Elguero, J. *J. Phys. Chem. A* **2008**, *112*, 7925.

JP806101T