

Interplay between halogen bonds and hydrogen bonds in OH/SH⋯HOX⋯HY (X = Cl, Br; Y = F, Cl, Br) complexes

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Abstract The character of the cooperativity between the HOX⋯OH/SH halogen bond (XB) and the Y—H⋯(H)OX hydrogen bond (HB) in OH/SH⋯HOX⋯HY (X = Cl, Br; Y = F, Cl, Br) complexes has been investigated by means of second-order Møller–Plesset perturbation theory (MP2) calculations and “quantum theory of atoms in molecules” (QTAIM) studies. The geometries of the complexes have been determined from the most negative electrostatic potentials ($V_{S,\min}$) and the most positive electrostatic potentials ($V_{S,\max}$) on the electron density contours of the individual species. The greater the $V_{S,\max}$ values of HY, the larger the interaction energies of halogen-bonded HOX⋯OH/SH in the termolecular complexes, indicating that the ability of cooperative effect of hydrogen bond on halogen bond are determined by $V_{S,\max}$ of HY. The interaction energies, binding distances, infrared vibrational frequencies, and electron densities ρ at the BCPs of the hydrogen bonds and halogen bonds prove that there is positive cooperativity between these bonds. The potentiation of hydrogen bonds on halogen bonds is greater than that of halogen bonds on hydrogen bonds. QTAIM studies have shown that the halogen bonds and hydrogen bonds are closed-shell noncovalent interactions, and both have greater electrostatic character in the termolecular species compared with the bimolecular species.

Keywords Cooperativity · Halogen bond · Hydrogen bond · Molecular electrostatic potentials · QTAIM

Introduction

During the last few decades, cooperative interactions between weak bonds (hydrogen bonds, halogen bonds, lithium

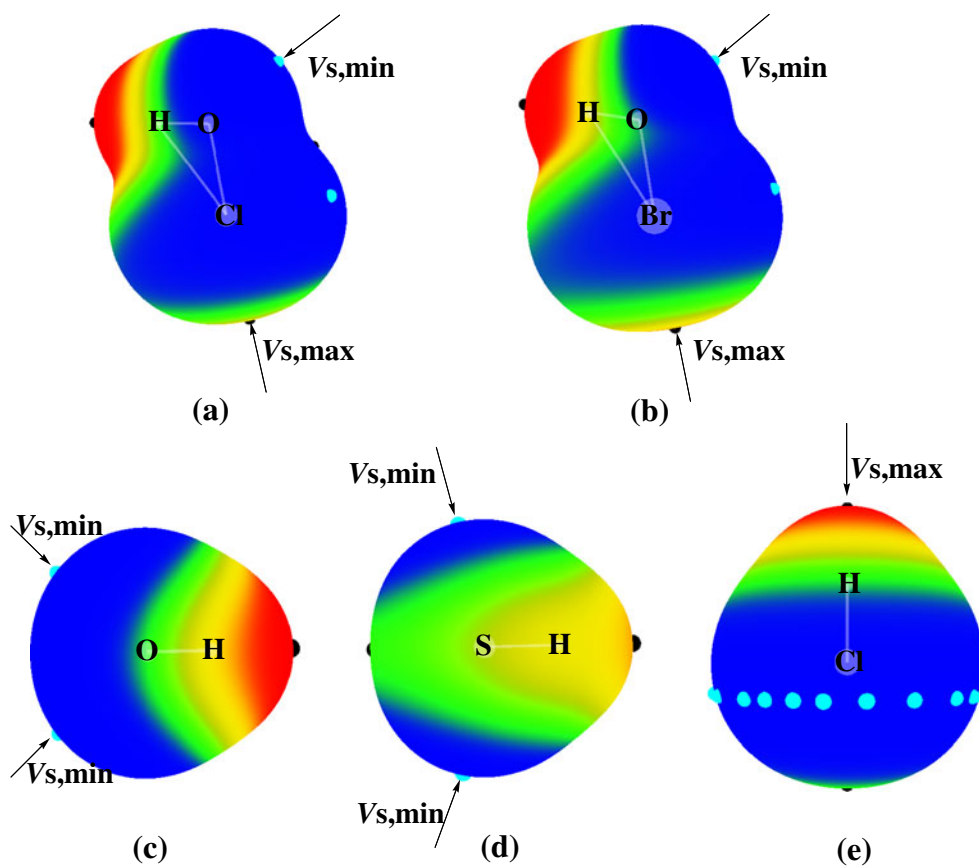
bonds, etc.) have attracted ever-increasing attention from researchers [1, 2] owing to their extensive applications in molecular biology [3–6], supermolecular chemistry [7], and crystal engineering [8–14], and so on. Cooperativity can be classified into two types, namely positive cooperativity, whereby a weak bond becomes stronger when the interactions exist in a polymolecular species ($n \geq 3$) compared to a bimolecular complex, and negative cooperativity, whereby a weak bond becomes weaker when the interactions exist in a polymolecular species compared to a bimolecular complex [15, 16]. In other words, positive cooperativity can stabilize a many-body structure, while negative cooperativity increases the total energy.

The hydrogen bond (HB) and halogen bond (XB) are the most typical weak bonds among noncovalent interactions [17]. The halogen bonding cooperative effect is very similar to the cooperativity of H-bonded systems; both effects are often responsible for the arrangement of molecules in crystals [18, 19]. The effects of halogen and hydrogen bonds upon each other can be explained by cooperativity [17–21]. Hypochlorous acid (HOCl) and hypobromous acid (HOBr) play critical roles in the human immune system [22]. They have the ability to kill invading pathogens through halogenation and oxidation. At high concentrations, HOCl can adjust cytokines to boost healing power, and HOBr can destroy disease histocytes [22, 23]. HOCl, as a source of the free radical $\cdot\text{OH}$, is very important in medical science, and HOBr accompanied by the free radical can fragment proteins [22, 24].

It is now well-established and generally accepted that the halogen bonding interaction results from the “ σ -hole” [25, 26], a position of deficiency of electron density of the covalently-bonded halogen atom on the extension of an R–X bond, through which the halogen atoms can interact attractively with negative sites, such as the lone pairs on Lewis bases. There are some obvious parallels between halogen bonding and hydrogen bonding, both are electrostatically-driven noncovalent interactions [26]. There is a region of positive electrostatic potentials (deficiency of electron

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Fig. 1 Electrostatic potentials on the 0.001 au molecular surfaces: **a** HOCl, **b** HOBr, **c** OH, **d** SH, **e** HCl. Color ranges, in kcal mol⁻¹: Red, more positive than 30; yellow, 10–30; green, 0–10; blue, negative. Position of $V_{S,max}$ is indicated in black and $V_{S,min}$ in blue



density) on the extension of an R-H bond, just like the “ σ -hole” of halogen atom.

It has been demonstrated that a variety of condensed phase physical properties that depend upon noncovalent interactions can be expressed analytically in terms of certain quantities that characterize the respective molecular surface electrostatic potentials $V_S(\mathbf{r})$ [27–29]. These quantities include the most positive and most negative values of $V_S(\mathbf{r})$ (denoted by $V_{S,max}$ and $V_{S,min}$). The $V_{S,max}$ of hydrogen atoms and halogen atoms and the $V_{S,min}$ of Lewis bases have been found to have good correlations with the interaction energies [30–35].

In this work, HOX (X = Cl, Br) has been selected as both the electron acceptor of halogen bonds and the electron donor of hydrogen bonds. Free radicals $\cdot\text{OH}$ and $\cdot\text{SH}$ have been selected to form HOX \cdots OH/SH halogen bonds with HOX, and HY (Y = F, Cl, Br) has been selected to form Y—H \cdots (H)OX hydrogen bonds with HOX. The OH/SH \cdots HOX \cdots HY (X = Cl, Br; Y = F, Cl, Br) complexes have been studied to explore the mutual influence of the HOX \cdots OH/SH halogen bonds and Y—H \cdots (H)OX hydrogen bonds. The quantum theory of atoms in molecules (QTAIM) method [36–38], which has been successfully applied to characterize various kinds of noncovalent interactions [34, 35], has been employed to analyze the cooperative effects of hydrogen bonds and halogen bonds.

Calculation methods

All calculations were performed with the Gaussian 03 program package [39]. The MP2/aug-cc-pVDZ [40–42] method, which has been applied to optimize the geometries and calculate the properties of a variety of hydrogen bonds and halogen bonds [43–45], was used to optimize the geometries of complexes and discrete species. The vibrational frequencies were then calculated at the same level to ensure that the equilibrium structures were real minima on the potential energy surfaces. The counterpoise procedure proposed by Boys and Bernardi [46] was used to correct the interaction energies (ΔE), excluding the inherent basis set superposition error (BSSE), as well as for geometry optimization and frequency computation. The topological properties at the

Table 1 The most positive ($V_{S,max}$, kcal mol⁻¹) and most negative ($V_{S,min}$, kcal mol⁻¹) electrostatic potentials in the monomers

	$V_{S,max}$	$V_{S,min}$
OH		-27.19
SH		-17.02
HOCl	23.01	-21.23
HOBr	32.27	-23.14
HF	75.67	
HCl	47.18	
HBr	39.86	

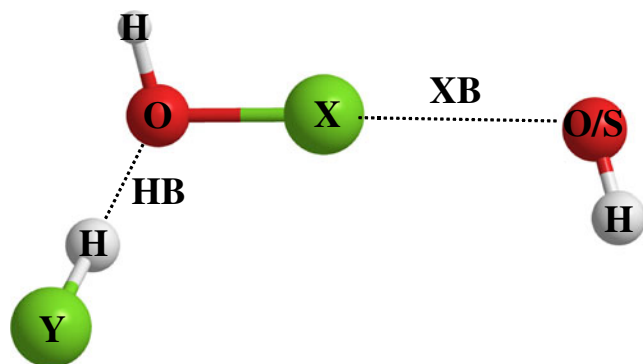


Fig. 2 The optimized geometry of the OH/SH...HOX...HY (X = Cl, Br; Y = F, Cl, Br) complex

bond critical points of the HBs and XBs were analyzed using the AIMAll program [47].

The electrostatic potential $V(\mathbf{r})$ that the electrons and nuclei of a molecule create at any point \mathbf{r} in the surrounding space is given by:

$$V(r) = \sum_A \frac{Z_A}{|R_A - r|} - \int \frac{\rho(r')dr'}{|r' - r|} \quad (1)$$

Z_A is the charge on nucleus A, located at \mathbf{R}_A , and $\rho(\mathbf{r})$ is the electronic density function of the molecule. $V(\mathbf{r})$ is positive in those regions in which the dominant contribution

is that of the nuclei, and negative where it is that of the electrons [31]. The electrostatic potential is a physical observable, which can be determined experimentally by diffraction techniques [48, 49] as well as computationally. In this work, the electrostatic potentials were calculated on the 0.001 a.u. (electrons/bohr³) contour of the molecule's electronic density [49] at the MP2/aug-cc-pVDZ level with the WFA surface analysis suite [50].

Results and discussion

Geometries, interaction energies, and frequencies

Geometries

Contour maps of the electrostatic potentials (ESP) of HOCl and HOBr are depicted in Fig. 1a and b. It can be seen that the Cl/Br atom displays a region of positive ESP on its outer side along the extension of the O—X bond, which contributes to the HOX...OH/SH halogen bond formed with ·OH/·SH, which has a negative ESP region on the outer side of the O/S atom (Fig. 1c). In addition, a large region of negative ESP can be observed on the outer side of the O atoms of HOCl and HOBr, as befits an O atom acting as the electron donor to form a Y—H...H(O)X hydrogen bond with the H atom of HY, which has a positive ESP region on the outer side of the H

Table 2 Interaction energies (in kJ/mol) of halogen-bonded and hydrogen-bonded bimolecular and termolecular complexes, as well as their changes

A...B...C	$\Delta E_{\text{total}}^a$	$\Delta E_{\text{X(D)}}^b$	$\Delta E_{\text{X(T)}}^c$	$\Delta E_{\text{H(D)}}^d$	$\Delta E_{\text{H(T)}}^e$	$\%E_{\text{X}}^f$	$\%E_{\text{H}}^g$	E_{coop}^h
OH...HOCl...HF	-20.41	-4.74	-7.64	-12.77	-15.67	61.27	22.74	-2.90
OH...HOCl...HCl	-15.76	-4.74	-6.76	-9.00	-11.02	42.71	22.49	-2.02
OH...HOCl...HBr	-14.30	-4.74	-6.60	-7.70	-9.56	39.28	24.19	-1.86
OH...HOBr...HF	-26.53	-7.99	-11.93	-14.60	-18.54	49.28	26.97	-3.94
OH...HOBr...HCl	-21.45	-7.99	-11.00	-10.45	-13.46	37.68	28.82	-3.01
OH...HOBr...HBr	-19.70	-7.99	-10.61	-9.09	-11.70	32.72	28.77	-2.62
SH...HOCl...HF	-22.15	-6.18	-9.38	-12.77	-15.97	51.87	25.08	-3.20
SH...HOCl...HCl	-17.60	-6.18	-8.60	-9.00	-11.42	39.24	26.93	-2.42
SH...HOCl...HBr	-16.09	-6.18	-8.40	-7.70	-9.92	35.97	28.86	-2.22
SH...HOBr...HF	-30.38	-10.63	-15.78	-14.60	-19.75	48.44	35.28	-5.15
SH...HOBr...HCl	-25.03	-10.63	-14.58	-10.45	-14.39	37.09	37.74	-3.94
SH...HOBr...HBr	-23.22	-10.63	-14.13	-9.09	-12.59	32.91	38.50	-3.50

$$^a \Delta E_{\text{total}} = E_{\text{ABC}} - E_{\text{A}} - E_{\text{B}} - E_{\text{C}}$$

$$^b \Delta E_{\text{X(D)}} = E_{\text{AB}} - E_{\text{A}} - E_{\text{B}}$$

$$^c \Delta E_{\text{X(T)}} = E_{\text{ABC}} - E_{\text{BC}} - E_{\text{A}}$$

$$^d \Delta E_{\text{H(D)}} = E_{\text{BC}} - E_{\text{B}} - E_{\text{C}}$$

$$^e \Delta E_{\text{H(T)}} = E_{\text{ABC}} - E_{\text{AB}} - E_{\text{C}}$$

$$^f \%E_{\text{X}} = (\Delta E_{\text{X(T)}} - \Delta E_{\text{X(D)}}) / \Delta E_{\text{X(D)}}$$

$$^g \%E_{\text{H}} = (\Delta E_{\text{H(T)}} - \Delta E_{\text{H(D)}}) / \Delta E_{\text{H(D)}}$$

$$^h E_{\text{coop}} = \Delta E_{\text{total}} - (\Delta E_{\text{X(D)}} + \Delta E_{\text{H(D)}})$$

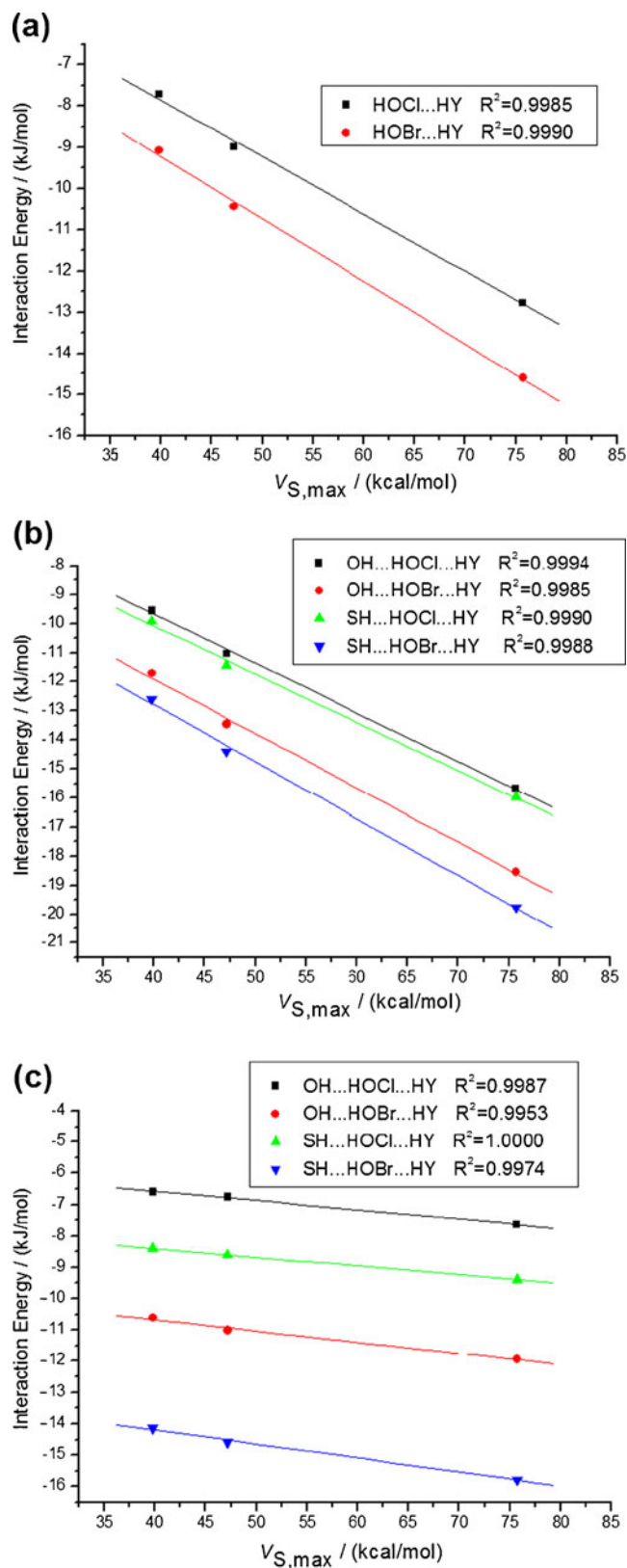


Fig. 3 Plots of interaction energies versus $V_{S,max}$ of HY: **a** $\Delta E_H(D)$ of $HOX...HY$ versus $V_{S,max}$ of HY, **b** $\Delta E_H(T)$ of $OH/SH...HOX...HY$ versus $V_{S,max}$ of HY, and **(c)** $\Delta E_X(T)$ of $OH/SH...HOX...HY$ versus $V_{S,max}$ of HY

atom (Fig. 1d). The most positive and most negative electrostatic potentials ($V_{S,max}$ and $V_{S,min}$) of $\cdot OH/\cdot SH$, HOX ($X = Cl, Br$), and HY ($Y = F, Cl, Br$) are listed in Table 1.

Figure 2 shows the optimized geometries of the complexes $OH/SH...HOX...HY$ ($X = Cl, Br$; $Y = F, Cl, Br$). The free radicals $\cdot OH$ and $\cdot SH$ are attracted to the X terminus of HOX to form a halogen bond, while the hydrogen atom in HY ($Y = F, Cl, Br$) is attracted to the O of HOX to form a hydrogen bond. The optimized geometries are in accordance with the ESP in Fig. 1.

Interaction energies

Table 2 shows the halogen-bonded and hydrogen-bonded interaction energies in bimolecular and termolecular complexes. A, B, and C denote $\cdot OH/\cdot SH$, $HOCl/HOBr$, and HY ($Y = F, Cl, Br$), respectively. The interaction energies of halogen-bonded bimolecular complexes, $\Delta E_X(D)$, range from -4.74 kJ/mol to -10.63 kJ/mol, while those of hydrogen-bonded bimolecular complexes ($\Delta E_H(D)$) range from -7.70 kJ/mol to -14.60 kJ/mol. Hence, the interaction energies of hydrogen-bonded bimolecular complexes are a little larger than those of halogen-bonded bimolecular complexes.

For halogen-bonded bimolecular complexes, the interaction energy $\Delta E_X(D)$ of $HOBr...OH/SH$ is larger than that of $HOCl...OH/SH$, which is in accordance with the observation that the most positive electrostatic potential of $HOBr$ (32.27 kcal mol $^{-1}$) is larger than that of $HOCl$ (23.01 kcal mol $^{-1}$) and thus the electron-accepting ability of $HOBr$ to form a halogen bond is greater than that of $HOCl$. For hydrogen-bonded bimolecular complexes, the interaction energies $\Delta E_H(D)$ of $Y-H...HOCl/HOBr$ decrease in the sequence $Y = F, Cl, Br$, which is in accordance with the observation that the most positive electrostatic potentials of HF, HCl, HBr ($75.67, 47.18,$ and 39.86 kcal mol $^{-1}$) decrease, and thus the electron-accepting ability of HY decreases in the sequence $Y = F, Cl, Br$.

From Table 2, it can be seen that when HY ($Y = F, Cl, Br$) is added to $HOX...OH/SH$ halogen bonds to form hydrogen bonds, the halogen-bonded interaction energies ($\Delta E_X(T)$) in the termolecular species become distinctly lower than those ($\Delta E_X(D)$) in the bimolecular species. For example, the halogen-bonded interaction energy is -4.74 kJ/mol in the bimolecular complex $HOCl...OH$ and becomes -7.64 kJ/mol in the termolecular complex $OH...HOCl...HF$, an increase of 61.27%. Similarly, the addition of a halogen bond has a great enhancing effect on a hydrogen bond. For example, the hydrogen-bonded interaction energy of the $F-H...(H)OCl$ is increased with the addition of the $HOCl...OH$ halogen bond in $OH...HOCl...HF$. The enhancing effects on the binding energies of hydrogen bonds on

Table 3 Binding distances of halogen bonds in dimers ($R_X(D)$, Å) and trimers ($R_X(T)$, Å), binding distances of hydrogen bonds in dimers ($R_H(D)$, Å) and trimers ($R_H(T)$, Å), changes of binding distances of halogen bonds (ΔR_X , Å) and hydrogen bonds (ΔR_H , Å) and the changing percentage of halogen bonds ($\% \Delta R_X$) and hydrogen bonds ($\% \Delta R_H$)

A...B...C	$R_X(D)$	$R_X(T)$	ΔR_X^a	$R_H(D)$	$R_H(T)$	ΔR_H^b	$\% \Delta R_X^c$	$\% \Delta R_H^d$
OH...HOCl...HF	2.9283	2.8257	-0.1026	1.8529	1.8208	-0.0321	-3.50	-1.73
OH...HOCl...HCl	2.9283	2.8477	-0.0806	2.0276	1.9777	-0.0499	-2.75	-2.46
OH...HOCl...HBr	2.9283	2.8679	-0.0604	2.0954	2.0426	-0.0528	-2.06	-2.52
OH...HOBr...HF	2.8905	2.7901	-0.1004	1.8258	1.7889	-0.0370	-3.47	-2.02
OH...HOBr...HCl	2.8905	2.8104	-0.0801	1.9827	1.9285	-0.0541	-2.77	-2.73
OH...HOBr...HBr	2.8905	2.8194	-0.0711	2.0454	1.9856	-0.0598	-2.46	-2.92
SH...HOCl...HF	3.2966	3.1498	-0.1468	1.8529	1.8158	-0.0371	-4.45	-2.00
SH...HOCl...HCl	3.2966	3.1819	-0.1147	2.0276	1.9736	-0.0540	-3.48	-2.66
SH...HOCl...HBr	3.2966	3.1925	-0.1041	2.0954	2.0401	-0.0553	-3.16	-2.64
SH...HOBr...HF	3.2131	3.0507	-0.1624	1.8258	1.7748	-0.0510	-5.05	-2.79
SH...HOBr...HCl	3.2131	3.0807	-0.1324	1.9827	1.9043	-0.0784	-4.12	-3.95
SH...HOBr...HBr	3.2131	3.0941	-0.1190	2.0454	1.9599	-0.0854	-3.70	-4.18

^a $\Delta R_X = R_X(T) - R_X(D)$

^b $\Delta R_H = R_H(T) - R_H(D)$

^c $\% \Delta R_X = \Delta R_X / R_X(D)$

^d $\% \Delta R_H = \Delta R_H / R_H(D)$

halogen bonds range from 32.72 % to 61.27 %, while those of halogen bonds on hydrogen bonds range from 22.49 % to 38.50 %. Therefore, the strengthening effects of hydrogen bonds on halogen bonds are greater than those of halogen bonds on hydrogen bonds.

Different hydrogen bonds have different influences on halogen bonds. For example, when the hydrogen bond varies from F—H... (H)OX, to Cl—H... (H)OX, to Br—H... (H)OX, the interaction energy of halogen-bonded HOCl...OH in the OH...HOCl...HY termolecular complexes varies from -7.64 kJ/mol, to -6.76 kJ/mol, to -6.60 kJ/mol, in accordance with the relative interaction energies of hydrogen-bonded F—H... (H)OX, Cl—H... (H)OX, and

Br—H... (H)OX (-12.77, -9.00, -7.70 kJ/mol). Likewise, different halogen bonds have different influences on hydrogen bonds. For example, the strengthening of the F—H... (H)OX hydrogen bond attributable to the HOCl...OH halogen bond of OH...HOCl...HF is 22.74 %, while the strengthening of the F—H... (H)OX hydrogen bond attributable to the halogen bond of OH...HOBr...HF is 26.97 %. These results are in accordance with the interaction energy of HOBr...OH (-7.99 kJ/mol) being greater than that of HOCl...OH (-4.74 kJ/mol). Similar trends are seen for other hydrogen bonds. From Table 2, it is clear that hydrogen bonds and halogen bonds make positive contributions to the interaction energies of one another, and that the

Table 4 Infrared vibration frequencies of halogen bonds in dimers ($\nu_X(D)$, cm^{-1}) and trimers ($\nu_X(T)$, cm^{-1}), vibration frequencies of hydrogen bonds in dimers ($\nu_H(D)$, cm^{-1}) and trimers ($\nu_H(T)$, cm^{-1}), as well as their changes

	$\nu_X(D)$	$\nu_X(T)$	$\Delta \nu_X^a$	$\nu_H(D)$	$\nu_H(T)$	$\Delta \nu_H^b$
OH...HOCl...HF	92.92	109.66	16.74	174.62	192.58	17.96
OH...HOCl...HCl	92.92	105.37	12.45	119.11	139.48	20.37
OH...HOCl...HBr	92.92	100.63	7.71	99.20	120.23	21.03
OH...HOBr...HF	102.94	116.68	13.74	183.47	205.61	22.14
OH...HOBr...HCl	102.94	113.74	10.80	126.07	149.76	23.69
OH...HOBr...HBr	102.94	112.22	9.28	104.08	131.04	26.96
SH...HOCl...HF	70.74	96.52	25.78	174.62	192.69	18.07
SH...HOCl...HCl	70.74	84.63	13.89	119.11	140.20	21.09
SH...HOCl...HBr	70.74	81.74	11.00	99.20	122.49	23.29
SH...HOBr...HF	77.70	95.61	17.91	183.47	212.82	29.35
SH...HOBr...HCl	77.70	89.86	12.16	126.07	157.16	31.09
SH...HOBr...HBr	77.70	88.11	10.41	104.08	137.73	33.65

^a $\Delta \nu_X = \nu_X(T) - \nu_X(D)$

^b $\Delta \nu_H = \nu_H(T) - \nu_H(D)$

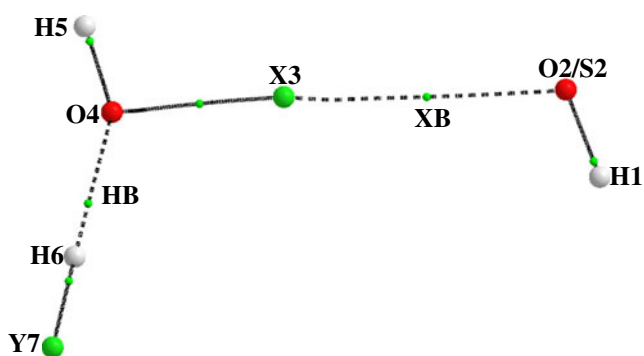


Fig. 4 The molecular graph of the OH/SH...HOX...HY (X = Cl, Br; Y = F, Cl, Br) complex

stronger the weak bond, the greater its cooperative effect on the other bond. From a two to a three body interaction, the enhancement of interaction energies show the positive cooperativity effect between HOX...OH/SH halogen bond and Y—H...(H)OX hydrogen bond in OH/SH...HOX...HY (X=Cl, Br; Y=F, Cl, Br) complexes.

Comparing $V_{S,max}$ of hydrogen atom of HY with hydrogen-bonded interaction energies $\Delta E_H(D)$ of Y—H...(H)OX, linear relationships were found with the correlation coefficients 0.9985 for Y—H...(H)OCl and 0.9990 for Y—H...(H)OBr, see Fig. 3a. Linear relationships were also found between $V_{S,max}$ of HY and hydrogen-bonded interaction energies $\Delta E_H(T)$ of Y—H...(H)OX in the OH/SH...HOX...HY termolecular complexes (Fig. 3b). The linear correlation coefficients are 0.9994, 0.9985, 0.9990, 0.9988 for the OH...HOCl...HY, OH...HOBr...HY, SH...HOCl...HY, SH...HOBr...HY complexes, respectively. The greater the $V_{S,max}$ values of HY, the larger the interaction energies of hydrogen-bonded Y—H...(H)OX in both the bimolecular and termolecular complexes.

Figure 3c displays the relationship of interaction energies of halogen-bonded HOX...OH/SH in the OH/SH...HOX...HY termolecular complexes and $V_{S,max}$ of hydrogen atom of HY. The linear correlation coefficients are 0.9987, 0.9953, 1.0000, 0.9974 for the OH...HOCl...HY, OH...HOBr...HY, SH...HOCl...HY, SH...HOBr...HY complexes, respectively. The greater the $V_{S,max}$ values of HY, the larger the interaction energies of halogen-bonded HOX...OH/SH in the termolecular complexes, indicating that the ability of cooperative effect of hydrogen bond on halogen bond are determined by $V_{S,max}$ of HY.

Binding distances

Table 3 presents the optimized binding distances of halogen bonds and hydrogen bonds in the bimolecular and termolecular complexes. The binding distances range from 2.7 to 3.3 Å for halogen bonds, and from 1.7 to 2.1 Å for hydrogen bonds. Compared to the bimolecular complexes, both the halogen bond and hydrogen bond distances are shortened in the termolecular complexes. For example, the length of the Br...S halogen bond in HOBr...SH is 3.2131 Å, and this decreases to 3.0507 Å with the addition of the F—H...(H)OX hydrogen bond. The change value ΔR_X is thus -0.1624 Å, and the percentage change value $\% \Delta R_X$ is -5.05 %. When an ·SH free radical was added to F—H...(H)OBr, forming a Br...S halogen bond, the F—H...(H)OX hydrogen bond length was shortened by 0.0510 Å from 1.8258 Å to 1.7748 Å. Irrespective of whether a hydrogen bond is added to a halogen bond or a halogen bond is added to a hydrogen bond, the binding distances of these weak bonds are shortened. The decreases in the binding distances of the halogen bonds are much larger than those in the hydrogen bonds. Furthermore, most percentage decreases in the binding distances of the halogen bonds ($\% \Delta R_X$) are larger than those of the hydrogen bonds ($\% \Delta R_H$).

Table 5 The electron density at BCPs of halogen bonds ($\rho_b(XB)$, a.u.) and hydrogen bonds ($\rho_b(HB)$, a.u.) as well as their changes

	$\rho_b(XB, D)$	$\rho_b(XB, T)$	$\Delta \rho_b(XB)$	$\rho_b(HB, D)$	$\rho_b(HB, T)$	$\Delta \rho_b(HB)$
OH...HOCl...HF	0.0115	0.0140	0.0025	0.0276	0.0300	0.0024
OH...HOCl...HCl	0.0115	0.0134	0.0019	0.0213	0.0238	0.0025
OH...HOCl...HBr	0.0115	0.0128	0.0013	0.0191	0.0213	0.0022
OH...HOBr...HF	0.0145	0.0176	0.0031	0.0295	0.0326	0.0030
OH...HOBr...HCl	0.0145	0.0169	0.0024	0.0235	0.0266	0.0031
OH...HOBr...HBr	0.0145	0.0166	0.0021	0.0212	0.0242	0.0030
SH...HOCl...HF	0.0104	0.0139	0.0036	0.0276	0.0304	0.0029
SH...HOCl...HCl	0.0104	0.0131	0.0027	0.0213	0.0241	0.0028
SH...HOCl...HBr	0.0104	0.0128	0.0024	0.0191	0.0216	0.0025
SH...HOBr...HF	0.0145	0.0201	0.0056	0.0295	0.0339	0.0043
SH...HOBr...HCl	0.0145	0.0189	0.0044	0.0235	0.0282	0.0047
SH...HOBr...HBr	0.0145	0.0184	0.0039	0.0212	0.0257	0.0045

Table 6 Topological and energy properties at the halogen bond critical points of the complexes (all values in a.u.)

	$\nabla^2\rho_b(\text{XB})$	$H_b(\text{XB})$	$G_b(\text{XB})$	$V_b(\text{XB})$	$-G_b(\text{XB})/$ $V_b(\text{XB})$	$\nabla^2\rho_b(\text{HB})$	$H_b(\text{HB})$	$G_b(\text{HB})$	$V_b(\text{HB})$	$-G_b(\text{HB})/$ $V_b(\text{HB})$
OH⋯HOCl⋯HF	0.0548	0.0014	0.0123	-0.0109	1.1297	0.1164	0.0013	0.0278	-0.0265	1.0481
OH⋯HOCl⋯HCl	0.0525	0.0014	0.0118	-0.0104	1.1315	0.0802	0.0016	0.0185	-0.0168	1.0951
OH⋯HOCl⋯HBr	0.0504	0.0013	0.0113	-0.0099	1.1359	0.0690	0.0016	0.0157	-0.0141	1.1104
OH⋯HOBr⋯HF	0.0638	0.0013	0.0146	-0.0133	1.1017	0.1232	0.0006	0.0302	-0.0297	1.0191
OH⋯HOBr⋯HCl	0.0614	0.0013	0.0140	-0.0127	1.1032	0.0886	0.0013	0.0208	-0.0195	1.0681
OH⋯HOBr⋯HBr	0.0603	0.0013	0.0138	-0.0125	1.1040	0.0778	0.0014	0.0180	-0.0166	1.0860
SH⋯HOCl⋯HF	0.0470	0.0015	0.0103	-0.0088	1.1678	0.1174	0.0011	0.0282	-0.0271	1.0422
SH⋯HOCl⋯HCl	0.0447	0.0015	0.0097	-0.0082	1.1823	0.0809	0.0016	0.0186	-0.0171	1.0917
SH⋯HOCl⋯HBr	0.0439	0.0015	0.0095	-0.0080	1.1872	0.0693	0.0015	0.0158	-0.0143	1.1064
SH⋯HOBr⋯HF	0.0561	0.0008	0.0132	-0.0124	1.0642	0.1260	0.0001	0.0314	-0.0312	1.0045
SH⋯HOBr⋯HCl	0.0540	0.0009	0.0126	-0.0116	1.0802	0.0929	0.0011	0.0221	-0.0210	1.0519
SH⋯HOBr⋯HBr	0.0530	0.0010	0.0123	-0.0113	1.0872	0.0819	0.0013	0.0192	-0.0179	1.0723

For halogen bonds, going from HF to HBr, $|\Delta R_X|$ becomes shorter. That is to say, the greater the $V_{S,\max}$ values of HY, the larger the $|\Delta R_X|$ value. Free radicals $\cdot\text{OH}$ and $\cdot\text{SH}$ also have significant effects on halogen bonds. $\cdot\text{SH}$ has much greater shortening effects on halogen bonds in termolecular species as compared to bimolecular species than $\cdot\text{OH}$. For hydrogen bonds, as the atomic mass number of the halogen atom of HY increases, $|\Delta R_H|$ is increased. Changing the free radical from $\cdot\text{OH}$ to $\cdot\text{SH}$ also affects the hydrogen bond length, with $|\Delta R_H|$ increasing going from $\text{OH}\cdots\text{HOX}\cdots\text{HY}$ to $\text{SH}\cdots\text{HOX}\cdots\text{HY}$. In terms of bond lengths, there is clear cooperativity between hydrogen bonds and halogen bonds, and the hydrogen bonds and halogen bonds in these systems enhance one another.

Frequencies

From the data in Table 4, it can be seen that the stretching vibration frequency of the halogen bond in $\text{HOCl}\cdots\text{OH}$ is 92.92 cm^{-1} while that in $\text{OH}\cdots\text{HOCl}\cdots\text{HF}$ is 109.66 cm^{-1} , representing a small blue shift. This is due to the addition of the $\text{F}-\text{H}\cdots(\text{H})\text{OX}$ hydrogen bond, which has an enhancing effect on the halogen bond $\text{HOCl}\cdots\text{OH}$. The stretching vibration frequency of the hydrogen bond in $\text{F}-\text{H}\cdots(\text{H})\text{OCl}$ is 174.62 cm^{-1} , and this is blue-shifted to 192.58 cm^{-1} in $\text{OH}\cdots\text{HOCl}\cdots\text{HF}$. The other complexes show similar trends.

Upon the addition of HX, the vibrational frequencies of halogen bonds show major changes. The interaction energies of hydrogen bonds formed by HF are stronger than those formed by HCl and HBr in $\text{OH}/\text{SH}\cdots\text{HOX}\cdots\text{HY}$, and

Table 7 The Laplacian of electron density at BCPS of halogen bonds ($\nabla^2\rho_b(\text{XB})$, a.u.) and hydrogen bonds ($\nabla^2\rho_b(\text{HB})$, a.u.) as well as their changes

	$\nabla^2\rho_b(\text{XB}, \text{D})$	$\nabla^2\rho_b(\text{XB}, \text{T})$	$\Delta\nabla^2\rho_b(\text{XB})$	$\nabla^2\rho_b(\text{HB}, \text{D})$	$\nabla^2\rho_b(\text{HB}, \text{T})$	$\Delta\nabla^2\rho_b(\text{HB})$
OH⋯HOCl⋯HF	0.0449	0.0548	0.0099	0.1093	0.1164	0.0071
OH⋯HOCl⋯HCl	0.0449	0.0525	0.0076	0.0718	0.0802	0.0084
OH⋯HOCl⋯HBr	0.0449	0.0504	0.0055	0.0611	0.0690	0.0079
OH⋯HOBr⋯HF	0.0525	0.0638	0.0113	0.1149	0.1232	0.0083
OH⋯HOBr⋯HCl	0.0525	0.0614	0.0088	0.0790	0.0886	0.0096
OH⋯HOBr⋯HBr	0.0525	0.0603	0.0078	0.0683	0.0778	0.0095
SH⋯HOCl⋯HF	0.0371	0.0470	0.0099	0.1093	0.1174	0.0081
SH⋯HOCl⋯HCl	0.0371	0.0447	0.0076	0.0718	0.0809	0.0091
SH⋯HOCl⋯HBr	0.0371	0.0439	0.0068	0.0611	0.0693	0.0082
SH⋯HOBr⋯HF	0.0449	0.0561	0.0112	0.1149	0.1260	0.0111
SH⋯HOBr⋯HCl	0.0449	0.0540	0.0091	0.0790	0.0929	0.0138
SH⋯HOBr⋯HBr	0.0449	0.0530	0.0081	0.0683	0.0819	0.0137

accordingly the changes in the vibrational frequencies of the halogen bonds $\Delta\nu_X$ induced by HF are also the largest. Upon the addition of $\cdot\text{OH}/\cdot\text{SH}$, the vibrational frequencies of the hydrogen bonds showed different modifications. The changes in the vibrational frequencies of the hydrogen bonds $\Delta\nu_H$ conformed to the order $\text{OH}/\text{SH}\cdots\text{HOX}\cdots\text{HF} < \text{OH}/\text{SH}\cdots\text{HOX}\cdots\text{HCl} < \text{OH}/\text{SH}\cdots\text{HOX}\cdots\text{HBr}$. Considering the different central molecules HOX, $\Delta\nu_H$ varies, with HOBr giving rise to larger changes than HOCl in the termolecular species.

In conclusion, adding HY to the $\text{X}\cdots\text{O}/\text{S}$ halogen bonds of $\text{HOX}\cdots\text{OH}/\text{SH}$ to form new hydrogen bonds enhances the vibrational frequencies of the halogen bonds. Similarly, adding $\cdot\text{OH}$ or $\cdot\text{SH}$ to the $\text{Y}-\text{H}\cdots\text{O}$ hydrogen bonds of $\text{Y}-\text{H}\cdots(\text{H})\text{OX}$ to form new halogen bonds also enhances the vibrational frequencies of the hydrogen bonds. There is thus positive cooperativity between the halogen bonds of $\text{HOX}\cdots\text{OH}/\text{SH}$ and the hydrogen bonds of $\text{Y}-\text{H}\cdots(\text{H})\text{OX}$. This is consistent with the changes in interaction energies and binding distances of these bonds.

QTAIM analyses

Many studies have indicated that QTAIM theory is very useful for studying the properties of conventional and unconventional interactions [51–53]. This theory has been applied here to analyze the characteristics of the cooperative effect between halogen bonds and hydrogen bonds.

Figure 4 shows molecular graphs of the complexes. The bond critical point (BCP) between O(2)/(S2) and X(3) indicates the formation of a halogen bond, and the BCP between O(4) and H(6) indicates the formation of a hydrogen bond.

The electron density ρ at the bond critical point (BCP) is a vital criterion in discussing the strength of a chemical bond. From Table 5, it can be seen that the electron densities at the BCPs in the termolecular complexes are a little larger than those in the bimolecular complexes for both halogen bonds and hydrogen bonds, indicating that the addition of a hydrogen bond strengthens the original halogen bond, and that the addition of a halogen bond strengthens the original hydrogen bond.

It is also evident that the closed-shell interactions, for which the electrostatic interaction is the primary influencing factor, have positive values of both $\nabla^2\rho_b$ and H_b , and that the value of $-G_b/V_b$ is larger than 1. When $\nabla^2\rho_b > 0$ and $H_b < 0$, the interaction is partly covalent [54, 55]. From the data in Table 6, it can be seen that the values of $\nabla^2\rho_b$, H_b , and $-G_b/V_b$ for both the halogen bonds and hydrogen bonds studied display the characteristics of closed-shell noncovalent interactions.

From the data in Table 7, for the halogen bonds, the values of $\nabla^2\rho_b(\text{XB})$ range from 0.0371 to 0.0525 in the bimolecular complexes and from 0.0439 to 0.0638 in the termolecular complexes. For the hydrogen bonds, the values of $\nabla^2\rho_b(\text{HB})$ range from 0.0611 to 0.1149 in the bimolecular complexes and from 0.0690 to 0.1260 in the termolecular complexes. Going

from a bimolecular to a termolecular complex, the $\nabla^2\rho_b(\text{XB})$ and $\nabla^2\rho_b(\text{HB})$ values at the BCPs of the same weak bonds become more positive, indicating that the addition of hydrogen bonds can impart the original halogen bonds with more electrostatic character, and the addition of halogen bonds likewise enhances the electrostatic character of the hydrogen bonds.

Conclusions

MP2/aug-cc-pVDZ calculations and QTAIM studies have been carried out on $\text{OH}/\text{SH}\cdots\text{HOX}\cdots\text{HY}$ ($\text{X}=\text{Cl}, \text{Br}$; $\text{Y}=\text{F}, \text{Cl}, \text{Br}$) complexes, and the cooperativity between $\text{HOX}\cdots\text{OH}/\text{SH}$ halogen bonds (XB) and $\text{Y}-\text{H}\cdots(\text{H})\text{OX}$ hydrogen bonds (HB) has been investigated. The following conclusions have been drawn:

- (1) The geometries of the complexes are determined by the most negative electrostatic potentials ($V_{S,\text{min}}$) and the most positive electrostatic potentials ($V_{S,\text{max}}$) on the electron density contours of the individual species.
- (2) The greater the $V_{S,\text{max}}$ values of HY, the larger the interaction energies of halogen-bonded $\text{HOX}\cdots\text{OH}/\text{SH}$ in the termolecular complexes, indicating that the ability of cooperative effect of hydrogen bond on halogen bond are determined by $V_{S,\text{max}}$ of HY.
- (3) From a two to a three body interaction, the enhancement of interaction energies show the positive cooperativity effect between $\text{HOX}\cdots\text{OH}/\text{SH}$ halogen bond and $\text{Y}-\text{H}\cdots(\text{H})\text{OX}$ hydrogen bond in $\text{OH}/\text{SH}\cdots\text{HOX}\cdots\text{HY}$ ($\text{X}=\text{Cl}, \text{Br}$; $\text{Y}=\text{F}, \text{Cl}, \text{Br}$) complexes.
- (4) The binding distances, infrared vibrational frequencies, and electron densities ρ at the BCPs of the hydrogen bonds and halogen bonds prove that there is positive cooperativity between these bonds. The potentiation of hydrogen bonds on halogen bonds is greater than that of halogen bonds on hydrogen bonds.
- (5) The halogen bonds and hydrogen bonds are closed-shell noncovalent interactions, and the electrostatic characters of both in termolecular complexes are greater compared with those in bimolecular complexes.

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