

## Halogen Bonding

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## Stabilizing Otherwise Unstable Anions with Halogen Bonding

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**Abstract:** Both hydrogen bonding (HB) and halogen bonding (XB) are essentially electrostatic interactions, but whereas hydrogen bonding has a well-documented record of stabilizing unstable anions, little is known about halogen bonding's ability to do so. Herein, we present a combined anion photoelectron spectroscopic and density functional theory study of the halogen bond-stabilization of the pyrazine (Pz) anion, an unstable anion in isolation due to its neutral counterpart having a negative electron affinity (EA). The halogen bond formed between the  $\sigma$ -hole on bromobenzene (BrPh) and the lone pair(s) of Pz significantly lowers the energies of the Pz-(BrPh)<sub>1</sub><sup>-</sup> and Pz-(BrPh)<sub>2</sub><sup>-</sup> anions relative to the neutral molecule, resulting in the emergence of a positive EA for the neutral complexes. As seen through its charge distribution and electrostatic potential analyses, the negative charge on Pz<sup>-</sup> is diluted due to the XB. Thermodynamics reveals that the low temperature of the supersonic expansion plays a key role in forming these complexes.

Being electron-withdrawing, covalently bonded halogens are often negatively charged in character. Surprisingly, they can interact attractively and directionally with nucleophiles such as lone pairs and anions.<sup>[1,2]</sup> This noncovalent interaction was first called halogen bonding (XB) by Dumas and co-workers.<sup>[3,4]</sup> The nature of XB was not resolved until 1992; covalently bonded, polarizable halogen atoms have positive electrostatic potential regions on the opposite end of the covalent bond and the equatorial sides of these atoms are negative.<sup>[5,6]</sup> XB is therefore attributed to the electrostatic attraction between this positive region and nucleophiles. The positive site was termed the  $\sigma$ -hole by Politzer et al. in 2007.<sup>[7]</sup> The size of the  $\sigma$ -hole depends on the polarizability of the halogen, that is, I > Br > Cl > F, but can also be tuned by other electron-withdrawing groups.<sup>[2,13]</sup>

Once its enigmatic nature was understood, XB was widely applied in supramolecular chemistry and crystal engineering as a driving force for self-assembly.<sup>[8–13]</sup> Gas phase experimental investigations of XB are scarce; they are limited to a handful of experiments using techniques such as molecular beam scattering,<sup>[14]</sup> rotational spectroscopy,<sup>[15–17]</sup> and black-

body infrared radiative dissociation.<sup>[18]</sup> Theoretical calculations, on the other hand, have been very fruitful.<sup>[1,2,19–23]</sup> According to Politzer, thermodynamics accounts for the rarity of gas phase studies;<sup>[1,24]</sup> that is, the Gibbs free energy,  $\Delta G = \Delta H - T\Delta S$ , has to be negative. The enthalpy change,  $\Delta H$ , is usually negative, yet due to entropy changes (loss of rotational and translational degrees of freedom) that occur upon forming a halogen bond, the  $T\Delta S$  term often has a large negative value, resulting in a positive  $\Delta G$ . Therefore, to construct XB in the gas phase, one needs to have an exothermic reaction at low temperatures.

Herein, we present a gas phase photoelectron spectroscopic study of the pyrazine anion (Pz<sup>-</sup>)-bromobenzene (BrPh) complexes. Pz is an *N*-heterocyclic molecule with two nitrogen atoms at the *para* positions of a six-membered ring, and it has been determined to have a negative electron affinity (EA) of  $-0.01$  eV,<sup>[25,26]</sup> implying that Pz<sup>-</sup> is unstable and difficult to form in isolation. Hydrogen bonding (HB) with water is a well-known means of stabilizing unstable anions.<sup>[26–31]</sup> Upon forming HB, the potential energy of the anion is lowered relative to the neutral species. This is due to a stronger interaction between water molecules and the anion than between water molecules and the anion's corresponding neutral species. As a result, the EA value switches from negative to positive. In this work, we have provided evidence that XB is formed between Pz<sup>-</sup> and BrPh, stabilizing unstable Pz<sup>-</sup> and rendering the EAs of neutral Pz(BrPh)<sub>*n*</sub> (*n* = 1, 2) positive. Density functional theory (DFT) calculations were performed for comparison with the experimental findings.

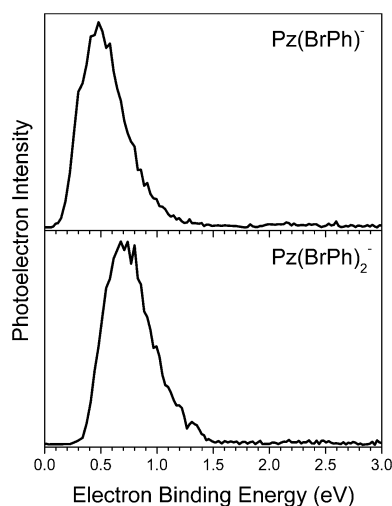
The details of experimental/computational methods are provided in the Supporting Information. The M06-2x functional<sup>[32]</sup> used is parameterized for dispersion and regarded as a standard method for describing non-covalent interactions such as XB.<sup>[33]</sup>

The mass spectra of Pz(BrPh)<sub>*n*</sub><sup>-</sup> (*n* = 1, 2) are provided in the Supporting Information. The photoelectron spectra of Pz(BrPh)<sub>*n*</sub><sup>-</sup> taken with a 355 nm (3.49 eV) laser are presented in Figure 1. For Pz(BrPh)<sub>1</sub><sup>-</sup>, the major electron binding energy (EBE) band ranges from 0.1 eV to 1.2 eV and peaks at 0.48 eV. For Pz(BrPh)<sub>2</sub><sup>-</sup>, it ranges from 0.3 eV to 1.5 eV and peaks at 0.69 eV. If there is sufficient Franck–Condon overlap between the ground state of the anion and the ground state of the neutral species and there is not much vibrational hot band intensity, the threshold of the EBE band is the EA. We extrapolate the lower EBE side of the band to zero, and the EBE values there, 0.15 eV and 0.32 eV, are taken as the experimental EA values of Pz(BrPh)<sub>1</sub> and Pz(BrPh)<sub>2</sub>, respectively. The EA of Pz(BrPh)<sub>1</sub> is not much above zero, suggesting that one BrPh molecule (one XB) is the threshold number that barely pulls the EA from negative to positive. The peak positions of the two spectra, 0.48 eV and 0.69 eV, are the experimental vertical detachment energies (VDE) for

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**Figure 1.** Photoelectron spectra of  $\text{Pz}(\text{BrPh})_n^-$  ( $n=1,2$ ) taken with a 355 nm (3.49 eV) laser.

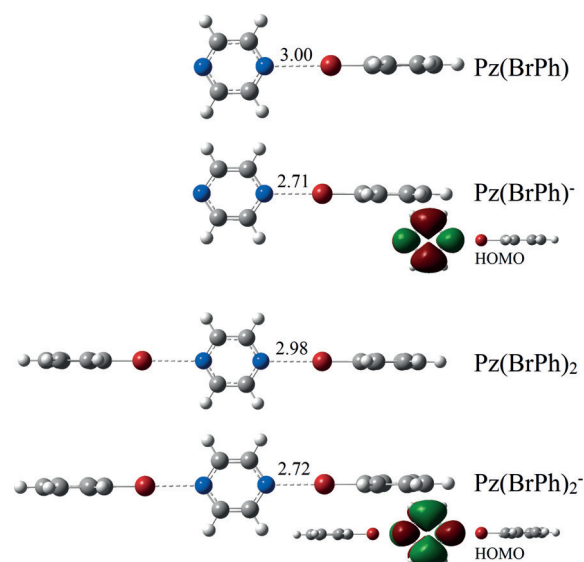
$\text{Pz}(\text{BrPh})_1^-$  and  $\text{Pz}(\text{BrPh})_2^-$ , respectively. The VDE is the photodetachment transition energy at which the Franck–Condon overlap between the wave functions of the anion and its neutral counterpart is maximal. These experimental results are tabulated in Table 1 for comparison with those obtained from calculations, and excellent agreement is observed. Gaussian fittings of these two spectra are provided in the Supporting Information.

**Table 1:** Experimental and theoretical EAs of  $\text{Pz}(\text{BrPh})_n$  and VDEs of  $\text{Pz}(\text{BrPh})_n^-$ . All values are in eV. ( $m=0,-$ )

	EA (Exp./Theo.)	VDE (Exp./Theo.)
$\text{Pz}(\text{BrPh})_m$	0.15/0.164	0.48/0.432
$\text{Pz}(\text{BrPh})_2^m$	0.32/0.331	0.69/0.664

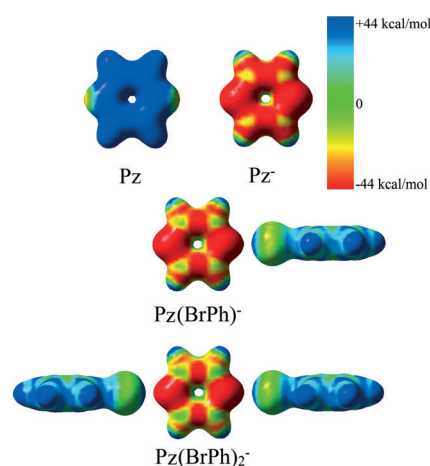
The calculated 3D coordinates of all the species are provided in the Supporting Information. Figure 2 presents the structures of  $\text{Pz}(\text{BrPh})_n^m$  ( $m=0,-$ ).  $\text{Pz}(\text{BrPh})_1^m$  possess  $C_{2v}$  symmetries with the Pz plane perpendicular to the BrPh plane. The bromine atom in BrPh and one of the nitrogen atoms of Pz form a XB. The XB length in the neutral complex is 3.00 Å, significantly longer than the 2.71 Å in the anion, indicating that the XB in the anion is stronger than in the neutral species. This is because the higher negative charge in the anion leads to stronger electrostatic attraction.  $\text{Pz}(\text{BrPh})_2^m$ , on the other hand, have  $D_{2h}$  symmetries. Each of the nitrogen atoms of Pz forms a XB with one BrPh molecule. The XB length in the anion (2.72 Å) is also shorter than that in the neutral species (2.98 Å). These bond lengths fall within the range of typical XB lengths.<sup>[1,2]</sup> The highest occupied molecular orbitals (HOMO) of  $\text{Pz}(\text{BrPh})_n^-$  have the excess electron occupying the  $\pi^*$  orbital of the Pz ring, indicating that the Pz moieties are indeed negatively charged.

Natural population analysis (NPA) provides another perspective for understanding the stabilization of  $\text{Pz}^-$  by XB. NPA shows that the net charge on the Pz ring is  $-0.93$  e in  $\text{Pz}(\text{BrPh})_1^-$  and  $-0.88$  e in  $\text{Pz}(\text{BrPh})_2^-$ . Therefore, the first XB



**Figure 2.** Calculated structures of  $\text{Pz}(\text{BrPh})_n^m$  ( $m=0,-$ ). The XB lengths are in Å. The highest occupied molecular orbitals (HOMO) are also presented.

decreases the charge by  $-0.07$  e, and the second further decreases the charge by  $-0.05$  e. To better visualize the XB, Figure 3 shows the electrostatic potential (ESP) surfaces of Pz,  $\text{Pz}^-$  and  $\text{Pz}(\text{BrPh})_n^-$ . The induced neutral (green), positive (blue), and negative (red) electrostatic potentials are mapped on the  $0.04$  e/bohr<sup>3</sup> surfaces in the range of  $\pm 44$  kcal mol<sup>-1</sup>. In neutral Pz, only the small ends of the nitrogen atoms show a negative potential due to their higher electronegativity. Upon electron attachment, the ESP of  $\text{Pz}^-$  has mostly negative potentials. In  $\text{Pz}(\text{BrPh})_1^-$ , in which one XB is present, the negative potentials (red) on the  $\text{Pz}^-$  ring decreases compared to bare  $\text{Pz}^-$ . When two XBs are formed in  $\text{Pz}(\text{BrPh})_2^-$ , the negative potential on  $\text{Pz}^-$  further decreases. These observations are consistent with the charge distribution change revealed by NPA. The positive  $\sigma$ -holes at



**Figure 3.** Electrostatic potential surfaces of Pz,  $\text{Pz}^-$ ,  $\text{Pz}(\text{BrPh})_1^-$ , and  $\text{Pz}(\text{BrPh})_2^-$ . The induced positive (blue), negative (red), and neutral (green) potentials are mapped on the  $0.04$  e/bohr<sup>3</sup> surfaces of the clusters.

the end of the Br atom (blue) and the negative equatorial side (yellow) can be clearly observed. The  $\sigma$ -holes directionally point towards the most negative (red) regions on the  $\text{Pz}^-$  ring, that is, the nitrogen atoms, forming the XB. Our theoretical effort in searching for other possible isomers, especially the  $\pi$ - $\sigma$  hole interaction, did not end in any stable local minima; this might be because the negative charge on the ring is mainly localized on the nitrogen atom in  $\text{Pz}^-$  ( $-0.65e$ ).

To quantify the stabilization effect of XB, the binding energies of the first and second XB of the neutral and anionic complexes,  $D_0[\text{Pz}(\text{BrPh})_n^m]$ , are given by:  $D_0[\text{Pz}(\text{BrPh})^m] = E[\text{Pz}^m] + E[\text{BrPh}] - E[\text{Pz}(\text{BrPh})^m]$  and  $D_0[\text{Pz}(\text{BrPh})_2^m] = E[\text{Pz}(\text{BrPh})^m] + E[\text{BrPh}] - E[\text{Pz}(\text{BrPh})_2^m]$  where  $E$  refers to the calculated energies with the zero-point energy corrected. In this case,  $D_0[\text{Pz}(\text{BrPh})^0]$  is 0.055 eV,  $D_0[\text{Pz}(\text{BrPh})^-]$  is 0.226 eV,  $D_0[\text{Pz}(\text{BrPh})_2^0]$  is 0.051 eV and  $D_0[\text{Pz}(\text{BrPh})_2^-]$  is 0.218 eV. The binding energies of the anions are higher than those of the neutral species, suggesting that upon forming the XB, the energy of the anions are lowered more than those of the neutral species, which switches the EA value from negative to positive. The higher negative charge on  $\text{Pz}^-$  compared to  $\text{Pz}$  causes stronger electrostatic attractions and shorter XBs in the anions.

Additionally, since  $D_0[\text{Pz}(\text{BrPh})^-] - D_0[\text{Pz}(\text{BrPh})^0] = \text{EA}[\text{Pz}(\text{BrPh})^0] - \text{EA}[\text{Pz}] = 0.171$  eV, and the calculated  $\text{EA}[\text{Pz}(\text{BrPh})^0]$  is 0.164 eV, we deduce that  $\text{EA}[\text{Pz}] = -0.007$  eV, which is consistent with the previously reported experimental value,  $-0.01$  eV.<sup>[25]</sup> Since accurate prediction of slightly negative EA values is difficult, this excellent agreement gives us confidence in the reliability of the theoretical methods used.

Finally, we discuss the thermodynamics of forming  $\text{Pz}(\text{BrPh})_n^m$ . Computed at 298 K, the internal energy change ( $\Delta E^0$ ), enthalpy change ( $\Delta H^0$ ), entropy change ( $\Delta S^0$ ), and Gibbs free energy change ( $\Delta G^0$ ) are tabulated in Table 2. Anion formation is more exothermic than that of the neutral species, which is consistent with the binding energy differences. At room temperature, none of these four complexes can form due to the positive  $\Delta G^0$ . Thus, we calculated the threshold temperature for each reaction to occur. Forming  $\text{Pz}(\text{BrPh})$  needs a temperature lower than 2.9 K, and the formation of  $\text{Pz}(\text{BrPh})_2$  is thermodynamically forbidden due to both the entropy loss and endothermicity. The formation of  $\text{Pz}(\text{BrPh})_1^-$  and  $\text{Pz}(\text{BrPh})_2^-$  needs temperatures lower than 124.3 K and 114.1 K, respectively. Gas phase supersonic expansion can usually cool the molecules to several tens of Kelvin,<sup>[34,35]</sup> which justifies our observation of the anions, although the neutral complexes will fall apart into  $\text{Pz}$  and  $\text{BrPh}$  molecules after photodetachment. This implies the

mechanism of forming the anions. Two pathways could be present: 1) The neutral  $\text{Pz}$  reacts with  $\text{BrPh}$  to form neutral complexes, which then attach electrons to form the anions. 2) The anionic  $\text{Pz}^-$  reacts with  $\text{BrPh}$  to form the anionic complexes. The first pathway is not realistic due to the very low temperatures needed to form the neutral complexes, hence, we speculate that even though  $\text{Pz}$  has a slightly negative EA, there are short-lived  $\text{Pz}^-$  anions formed in the ion source, which are then stabilized by forming the XB.

In general, HB and XB are considered to be two parallel worlds,<sup>[36,37]</sup> so the binding circumstances of HB should be largely applicable to XB. However, there are still many missing pieces in studies of XB compared to HB. For example, we recently designed anionic, metallic XB acceptors, which have long been known to exist for HB but have been unknown for XB.<sup>[38]</sup> In this work, we for the first time extend XB to stabilizing gas-phase unstable anions, which is already well-known in the case of HB.<sup>[26-31]</sup>

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## Conflict of interest

The authors declare no conflict of interest.

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**Table 2:** Computed thermodynamic properties ( $\text{kcal mol}^{-1}$ ) for gas-phase complex formation at 298 K. The threshold temperatures (K) for the reactions to occur are also listed.

Reactions	$\Delta E^0$	$\Delta H^0$	$T\Delta S^0$	$\Delta G^0$	Threshold T
$\text{Pz} + \text{BrPh} \rightarrow \text{Pz}(\text{BrPh})$	-0.1	-0.7	-10.2	9.5	2.9
$\text{Pz}^- + \text{BrPh} \rightarrow \text{Pz}(\text{BrPh})^-$	-4.1	-4.7	-10.5	5.8	124.3
$\text{Pz}(\text{BrPh}) + \text{BrPh} \rightarrow \text{Pz}(\text{BrPh})_2$	0.15	-0.45	-10.1	9.6	Won't occur
$\text{Pz}(\text{BrPh})^- + \text{BrPh} \rightarrow \text{Pz}(\text{BrPh})_2^-$	-3.8	-4.4	-10.4	6.1	114.1

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