Published in final edited form as:

Chemistry. 2016 December 05; 22(49): 17690–17695. doi:10.1002/chem.201603674.

Exploring the (Very Flat) Potential Energy Landscape of R-Br... π Interactions with Accurate CCSD(T) and SAPT Techniques

Kevin E. Riley, Mariela Vazquez, Cole Umemura, Christopher Miller, and Khanh-An Tran

Abstract

Halogen bonds involving an aromatic moiety as an acceptor, otherwise known as R-X... π interactions, have increasingly been recognized as being important in materials and in protein-ligand complexes. These types of interactions have been the subject of many recent investigations, but little is known about the ways in which the strengths of R-X... π interactions vary as a function of the relative geometries of the interacting pairs. Here we use the accurate CCSD(T) and SAPT2+3 δ MP2 methods to investigate the potential energy landscapes for systems of HBr, HCCBr, and NCBBr complexed with benzene. It is found that only the separation between the complexed molecules have a strong effect on interaction strength while other geometric parameters, such as tilting and shifting R-Br... π donor relative to the benzene plane, affect these interactions only mildly. Importantly, it is found that the C_{6v} (T-shaped) configuration is not the global minimum for any of the dimers investigated.

Introduction

Halogen bonds have been recognized in the past decade as playing important roles in many areas of chemistry and material science,^{1–7} and these directional interactions have been of particular interest in biomolecular^{7–12} and crystalline structures.^{13–15} A halogen bond is a short-range RX...YZ interaction, where X is a halogen (typically chlorine, bromine, or iodine) that is part of the molecule RX and YZ is a Lewis base; Y is often an atom, such as oxygen, nitrogen, or sulfur, that has a lone pair. Halogen bonds can be said to be analogous in many ways to hydrogen bonds (of the form RH...YZ). In both hydrogen bonding and halogen bonding, the donor (R) and the acceptor (Y) tend to be electronegative.¹

The electrostatic attraction between the σ -hole, a region of positive potential located along the extension of the R-X bond, and the negative Lewis base is the origin of halogen bonding.^{1–3} As halogens are large atoms with high polarizabilities, dispersion also plays a large role in stabilizing these interactions.⁴ It has recently been recognized that aromatic groups can serve as halogen bond acceptors, forming what we refer to here as R-X... π interactions.^{16–21} These types of noncovalent interactions have been observed in the structures of crystalline materials and in protein-ligand complexes in which aromatic amino acids (phenylalanine, tyrosine, tryptophan) serve as R-X... π acceptors.^{11,16,22,23} The dependence of “standard” halogen bonds on geometric factors has been studied extensively and has been very well characterized computationally.^{4,24–27} Conversely, very little is known about the ways in which the strength and character of R-X... π interactions vary as a function of geometric parameters.

In this work we investigate the potential energy landscapes of R-Br...C₆H₆ interactions in order to elucidate the ways that R-X... π interactions depend on the relative orientation of the interacting pair. Based on crystallographic evidence obtained for supramolecular structures and protein-ligand complexes it is clear that R-X... π interactions rarely adopt a purely T-shaped (C_{6v}) configuration, in which the R-X bond is perpendicular to, and pointed directly towards the center of the π system.^{11,16,20} Of course, the orientation of a R-X... π interaction in one of these systems is governed not only by the potential energy landscape of the R-X... π interaction itself, but is also strongly affected by other noncovalent interactions and steric restrictions imposed by the surrounding environment. In a recent study by Herrebout and coworkers a set of F₃CX...C₆H₆ and F₃CX...Toluene complexes is investigated using both microwave spectroscopy and MP2/aug-cc-pVDZ calculations.²⁰ In this study it is indicated that the minimum energy conformation for these complexes is not the T-shaped structure but rather a structure in which the halogen is pointed roughly towards one of the benzene carbons.

There are two main factors that control the size and charge of a halogen's σ -hole, thus modulating the strength of a C-X... π interaction. The first of these is the identity of the halogen, with larger halogens having the tendency to form larger σ -holes (I > Br > Cl).¹⁻³ The other factor affecting the size of the σ -hole is the chemical environment in which the halogen is found, with the electronegativity of neighboring atoms having the largest impact on σ -hole size.^{1-3,24} Thus, a halogen bound to an electron withdrawing group, such as the -CN, will tend to have a larger, more positive, σ -hole than one bound to (for example) an aliphatic carbon. This ability to modulate, or "tune," the strength of a halogen bond, or R-X... π interaction, by making substitutions of electronegative or electropositive groups near the halogen has been studied extensively and it has been shown that it is mainly attributable to modulation of the electrostatic contribution to the overall interaction.^{24,28,29} Tunability is a property of these interactions that shows great promise for the design of materials with novel properties and in the development of pharmaceutical ligands.

For all R-X...C₆H₆ complexes considered in this study, there are three principal geometric parameters that are of interest (Figure 1), these are the distance from the bromine to the benzene plane (R1), the distance from the benzene centroid to the projection of the bromine onto the benzene plane (R2, i.e. distance from centroid to point "directly below" the bromine on the benzene plane), and the angle established by the bromine projection on the benzene plane, the bromine itself, and the atom to which bromine is bound ($\angle$ (R-Br... π)).

Three bromine-containing R-Br... π donor molecules are considered here: HBr, HCCBr, and NCBr; benzene is used as the R-Br... π acceptor. These three molecules were chosen because of the fact that they are linear, which reduces the effect of secondary (non-R-Br... π) interactions in stabilizing the R-Br...C₆H₆ complexes and because the three molecules have σ -holes that differ distinctly in size and charge (Figure 2). Thus, the effect of σ -hole size on the relative geometries of R-X... π interactions, as well as binding energetics, are investigated here.

Results and Discussion

Figure 3 gives CCSD(T)/aQZ and SAPT2+36MP2/aTZ potential energy curves as a function of the distance between bromine and the benzene centroid in the C_{6v} configuration (R_1). Here it is seen that, as expected, the R-Br... π interactions become stronger with increasing σ -hole size and charge (i.e. $E(\text{HBr}) > E(\text{HCCBr}) > E(\text{NCBr})$), with a corresponding slight decrease in the equilibrium separation between molecules ($R_{1\text{eq}}$). CCSD(T) equilibrium interaction energies increase from -2.06 kcal/mol (HBr, $R_{1\text{eq}} = 3.52\text{\AA}$) to -3.00 kcal/mol (HCCBr, $R_{1\text{eq}} = 3.43\text{\AA}$) to -4.01 kcal/mol (NCBr, $R_{1\text{eq}} = 3.36\text{\AA}$). The SAPT potential energy curves are in good agreement with those produced at the CCSD(T) level, with slight underbinding behavior at shorter R_1 distances.

In Figure 3 can also be seen the SAPT2+36MP2/aTZ contributions to the interaction energy. As has been reported in a previous study, dispersion is the strongest contributor to attraction in these interactions, which is not surprising given the high polarizabilities of benzene and bromine.²¹ Electrostatics also plays an important role in attraction and is largely responsible for modulating the strength of these R-Br... π interactions. The induction term, to a lesser extent, also plays a role in modulating R-Br... π interaction strength. The dispersion and exchange terms are largely unchanged for the three R-Br... π donors. This finding is in good agreement with results previously reported for halogen bonds and R-X... π interactions.

CCSD(T) and SAPT potential energy curves for tilting of the R-Br... π donor above the benzene plane (i.e. varying $a(\text{R-Br...}\pi)$) are shown in Figure 4. Here R-X... π donors are located directly above the benzene centroid with the bromine at a fixed R_1 distance corresponding to the SAPT C_{6v} minimum (HBr: $3.56\text{\AA}$; HCCBr: $3.46\text{\AA}$; NCBr: $3.38\text{\AA}$). It is observed that the potential energy minimum for these structures occurs when the complex adopts its T-shape configuration. The complexes are destabilized upon rotation (tilting) of the C-Br... π donor, however this destabilization occurs rather slowly; at a R-Br... π angle of 155° the NCBr... C_6H_6 , HCCBr... C_6H_6 , and HBr... C_6H_6 complexes are destabilized by 0.24 (6.1%), 0.22 (7.4%), and 0.20 (9.7%) kcal/mol, respectively, destabilizations that are less than 10% of the C_{6v} binding energies (computed at CCSD(T) level). At an R-Br... π angle of 140° (the largest angle investigated here) NCBr... C_6H_6 , HCCBr... C_6H_6 , and HBr... C_6H_6 are destabilized by 0.56 (13.9%), 0.50 (16.8%), and 0.46 (22.5%) kcal/mol, respectively. Interestingly, the amount by which the dimers are destabilized upon tilting of the R-Br... π donor does not seem to strongly depend on the size and charge of the bromine σ -hole, with binding energies diminishing by very similar amounts for all three complexes.

Once again, CCSD(T) and SAPT results are in good agreement, with SAPT slightly underbinding throughout these curves. It should be noted that the quality of the SAPT description improves with increasing σ -hole size, with the closest agreement between methods occurring for NCBr... C_6H_6 . The reason for this trend is most likely the incomplete description of dispersion contributions offered by the SAPT method. As dispersion plays the largest role, in terms of fractional contribution, to attraction in HBr... C_6H_6 , this complex exhibits the poorest agreement with accurate CCSD(T) binding energies.

SAPT interaction energy contribution terms for tilting of R-Br... π donors from their C_{6v} conformations at a fixed R1 distance of 3.4 Å are given in Figure 4. The most interesting aspect of the data depicted here is the fact that the attractive electrostatic and induction interaction components remain almost completely flat throughout the range of angles. The exchange and dispersion binding contributions, conversely, vary significantly, with the exchange term becoming more repulsive, and dispersion becoming more attractive, as this angle decreases. The most significant effect is seen for exchange, which increases (becomes more repulsive) by approximately 0.75–0.85 kcal/mol through the 40° rotation.

It has been traditionally held that the electrostatic interaction is primarily responsible for the directionality of halogen bonds. This is perhaps the most intuitively satisfying way to explain the preferred R-X...Y angle of 180° in a halogen bond, as it can be pictured as the halogen σ -hole tilting toward the halogen bond acceptor, resulting in halogen bond stabilization. This assumption has recently been questioned in several studies.^{26,27,30} In a recent work, Stone systematically investigates the effect of halogen bond rotation for several small halogen bonding complexes, such as F-Cl...F-H, considering both the F-Cl-F and Cl-F-H angles, on the SAPT interaction energy terms (other complexes are also studied).²⁶ In this study it is found that the exchange-repulsion term varies strongly as a function of F-Cl-F bending while the electrostatic term is almost completely flat. The reason for the strong involvement of exchange-repulsion effects in halogen bond directionality involves the oblate shape of a bound halogen's electron density envelope, with the halogen's radius in the direction of its covalent bond being smaller than its radius perpendicular to the bond. Rotation of the halogen bond geometry away from linearity results in a higher amount of overlap between the electron densities of the halogen and the halogen bond acceptor, bringing about a larger exchange-repulsion contribution.

Here we find that, in terms of SAPT interaction energy contributions, the reasons for R-X... π directionality parallel those for halogen bond directionality, as described by Stone and others.^{26,27,30} The main difference is that, in Stone's halogen bond study, dispersion contributions generally tend to remain flat, whereas for these R-X... π interactions this term becomes more attractive throughout the rotation range by approximately 0.25–0.30 kcal/mol. It stands to reason that small changes in the orientation of the oblate halogen near the benzene surface would have a stronger effect in R-X... π interactions than in halogen bonds, as dispersion plays a larger role in stabilizing these interactions because of the larger amount of contact, and electron density overlap, between the complexed molecules.

It is interesting to note that, at this fixed distance of 3.4 Å, each of the SAPT terms shifts up or down with increased σ -hole size. The reasoning for shifts in the electrostatic and induction terms are straightforward, as these terms would obviously become more attractive as the charge of the σ -hole increases. The reason for the decrease in the magnitude of the exchange term with growing σ -hole size, with HBr...C₆H₆ having the largest exchange term value, is more interesting. This effect is caused by polar flattening, with the bromine electron density envelope in HBr...C₆H₆ having a greater spatial extent along the extension of the H-Br bond than the other two molecules.^{26,31} NCB...C₆H₆ has the greatest amount of polar flattening, thus its exchange contribution is the smallest of the three R-Br... π donors. At this scale, dispersion results are probably not reliable, as discussed above. It is expected that

HBr...C₆H₆ should have the largest contribution from dispersion, for reasons paralleling those described for the exchange term.

Figure 5 gives CCSD(T) and SAPT potential energy curves for shifting the R-Br... π donor across the benzene surface at a R1 distance corresponding to the SAPT C_{6v} R1 minimum (i.e. varying R2). The most noteworthy aspect of the data presented here is the flatness of the curves from the C_{6v} position out to a distance of 1.21 Å, corresponding to a position directly above the benzene C=C bond. Beyond this point, the strengths of the interactions decrease fairly sharply as the donor molecules move outside the aromatic region. The sharpness of complex destabilization in the region from 1.21 Å to 1.50 Å increases with increasing σ -hole size, a trend that is most likely attributable to shorter R-Br... π distances (R1). The C_{6v} configuration does not represent a minimum on these potential energy curves, with CCSD(T) minima occurring at R2 distances of 0.51 Å (−2.06 kcal/mol), 0.72 Å (−3.04 kcal/mol), and 0.63 Å (−4.05 kcal/mol) for HBr...C₆H₆, HCCBr...C₆H₆, and NCCBr...C₆H₆, respectively. Interestingly, minima along the R2 coordinate do not follow a pattern prescribed by σ -hole size, with NCCBr...C₆H₆ having an intermediate R2 minimum. It should be noted, however, that the potential wells along this coordinate are extremely shallow (up to approximately 0.05 kcal/mol), meaning that the location of the minimum energy should be unusually sensitive to the position of the interacting pair.

SAPT interaction energy contributions for potential energy curves corresponding to variation of the R2 distance are given in Figure 5. Here it is seen that, as in the case of R-Br... π donor tilting, the dispersion and exchange terms are much stronger functions of this parameter than the electrostatic and induction terms. Dispersion consistently becomes less attractive with an increasing R2 distance, increasing by approximately 0.70–0.75 kcal/mol within the range considered here. This behavior seems reasonable, as the C_{6v} configuration of these dimers will give rise to the greatest contact area (overlap) between bromine and the benzene ring, resulting in a large dispersion component; shifting bromine away from the benzene centroid will result in less contact area, and thus less dispersion attraction, between the two molecules. For each of the three complexes, the exchange term is very flat out to an R2 distance of about 0.8 Å, after which it decreases fairly sharply as the R-Br... π donor passes beyond benzene's region of highest electron density. For all three complexes, the electrostatic and induction terms both become slightly more attractive as the R2 distance increases. The electrostatic terms reach a minimum in the range between 0.7 Å and 0.9 Å. For all complexes the induction term reaches a minimum at an R2 distance of 1.2 Å. Potential wells for both electrostatic and induction terms are about 0.1–0.15 kcal/mol deep (comparing minimum to C_{6v} geometry). These two terms likely become more attractive as the R2 distance approaches a position approximately above the C=C bond, a region of high electron density. This ring of slightly enhanced negative charge, found at a radial distance of about 0.9 Å, is not obvious in the electrostatic potential given in Figure 2, but is seen upon rescaling the potential map.

Conclusions

In summary, we have shown that the potential energy landscape for R-Br... π interactions is very flat, with the distance of separation between the interacting molecules (R1) being the

only parameter to strongly influence the interaction strength. Tilting the R-Br... π donor above the benzene plane (relative to the C_{6v} structure) weakens the interaction fairly slowly. SAPT analysis indicates that exchange repulsion is responsible for the interaction becoming weaker upon tilting, a trend attributable to bromine's oblate shape. Interestingly, the degree of destabilization upon tilting exhibited in the three complexes considered here is very similar and does not strongly depend on σ -hole size. The potential energy curve for shifting the R-Br... π donor across the benzene plane is very flat until the donor passes the spatial extent of the aromatic ring (i.e. out to a distance $R_2 = 1.21 \text{ \AA}$). Each of the complexes becomes slightly more stable as the R_2 distance is increased, with minima occurring between R_2 distances of 0.5 and 0.75 $\text{\AA}$, meaning that the C_{6v} orientation is found not to correspond to a potential energy minimum for any of these R-Br... π complexes. The SAPT contribution terms are only weakly affected by R-Br... π donor shifting, with dispersion being the most strongly influenced term.

Computational Methods

All dimer structures were initially optimized at the MP2/def2-TZVP level of theory. CCSD(T) and SAPT potential energy curves are based on the geometries obtained in these optimizations and the rigid-monomer approximation is used.

Because of the prohibitive computational cost, it is not possible to directly compute CCSD(T)/aQZ binding energies, instead, estimates of the CCSD(T)/aQZ binding energies are computed using the following equation:

$$\Delta E [\text{CCSD (T) /aQZ}] \approx \Delta E [\text{MP2/aQZ}] + (\Delta E [\text{CCSD (T) /aDZ}] - \Delta E [\text{MP2/aDZ}])$$

This strategy of estimation has been shown to produce very accurate results and makes use of the fact that the MP2 and CCSD(T) methods show very similar basis set dependence (i.e.

$E[\text{CCSD(T)/aQZ}] - E[\text{CCSD(T)/aDZ}] = E[\text{MP2/aQZ}] - E[\text{MP2/aDZ}]$).³² aQZ denotes aug-cc-pVQZ(-PP) and aDZ refers to the aug-cc-pVDZ(-PP) basis set. Standard Dunning type basis sets are used for all CCSD(T) and MP2 computations. Because relativistic effects can be important in describing large atoms, the aug-cc-pVDZ-PP and aug-cc-pVQZ-PP basis sets, which include pseudopotentials that implicitly describe relativistic effects, are used on bromine for all CCSD(T) and MP2 calculations. The counterpoise correction scheme is used to account for basis set superposition error in all MP2 and CCSD(T) computations.

The SAPT2+3 δ MP2/aTZ method is used to obtain accurate interaction energies that are divided into contributions from electrostatics, dispersion, induction, and exchange-repulsion terms.^{33–35} Here SAPT2+3 δ MP2/aTZ is benchmarked against CCSD(T) results and is shown to provide very accurate binding energies. SAPT2+3 δ MP2/aTZ is a third-order SAPT method that includes third-order HF induction contributions and third-order MP2 contributions to induction and dispersion.

Electrostatic potential maps are produced on the molecular ‘surface,’ taken to be the 0.001 electron/bohr contour of the molecule’s electron density. Molecular electronic densities are computed at the B3LYP/6-311G* level of theory.

All CCSD(T) and MP2 computations are made using the Molpro³⁶ suite of molecular electronic structure programs while SAPT calculations are made using the Psi4 package.³⁷ Molecular electrostatic potential maps are produced using Spartan molecular electronic structure program.³⁸

Acknowledgments

The authors gratefully acknowledge support from the NSF HBCU-UP program (HRD-1505219), the NIH R15 program (1R15GM113193 - 01), the NIH RISE program (5R25GM060926-10), and the NSF BUILD program (5RL5GM118966-03).

References

1. Politzer P, Lane P, Concha MC, Ma Y, Murray JS. J Mol Model. 2007; 13:305–311. [PubMed: 17013631]
2. Politzer P, Murray JS, Clark T. Phys Chem Chem Phys. 2013; 15:11178–11189. [PubMed: 23450152]
3. Murray JS, Riley KE, Politzer P, Clark T. Aust J Chem. 2010; 63:1598–1607.
4. Riley KE, Hobza P. J Chem Theory Comput. 2008; 4:232–242. [PubMed: 26620655]
5. Cavallo G, Metrangolo P, Milani R, Pilati T, Priimagi A, Resnati G, Terraneo G. Chem Rev. 2016; 116:2478–2601. [PubMed: 26812185]
6. Kolá MH, Hobza P. Chem Rev. 2016; 116:5155–5187. [PubMed: 26840433]
7. Gilday LC, Robinson SW, Barendt TA, Langton MJ, Mullaney BR, Beer PD. Chem Rev. 2015; 115:7118–7195. [PubMed: 26165273]
8. Riley KE, Hobza P. Cryst Growth Des. 2011; 11:4272–4278.
9. Parisini E, Metrangolo P, Pilati T, Resnati G, Terraneo G. Chem Soc Rev. 2011; 40:2267–2278. [PubMed: 21365086]
10. Scholfield MR, Vander Zanden CM, Carter M, Ho PS. Protein Sci. 2013; 22:139–152. [PubMed: 23225628]
11. Lu Y, Wang Y, Zhu W. Phys Chem Chem Phys. 2010; 12:4543–4551. [PubMed: 20428531]
12. Wilcken R, Zimmermann MO, Lange A, Joerger AC, Boeckler FM. J Med Chem. 2013; 56:1363–1388. [PubMed: 23145854]
13. Aackeröy CB, Wijethunga TK, Desper J, akovi M. Cryst Growth Des. 2015; 15:3853–3861.
14. Mukherjee A, Tothadi S, Desiraju GR. Acc Chem Res. 2014; 47:2514–2524. [PubMed: 25134974]
15. Aackeröy CB, Hurley DP, Desper J. Cryst Growth Des. 2012; 12:5806–5814.
16. Lu YX, Zou JW, Wang YH, Yu QS. Chem Phys. 2006; 334:1–7.
17. Karthikeyan S, Lee JY. Chem Phys Lett. 2014; 602:16–21.
18. Forni A, Pieraccini S, Rendine F, Gabas S, Sironi M. ChemPhysChem. 2012; 13:4224–4234. [PubMed: 23169496]
19. Forni A, Pieraccini S, Rendine S, Sironi M. J Comput Chem. 2014; 35:386–394. [PubMed: 24339225]
20. Nagels N, Hauchecorne D, Herrebout WA. Molecules. 2013; 18:6829–6851. [PubMed: 23752468]
21. Riley KE, Ford CL, Demouchet K. Chem Phys Lett. 2015; 621:165–170.
22. Xu Z, Yang Z, Liu Y, Lu Y, Chen K, Zhu W. J Chem Inf Model. 2014; 54:69–78. [PubMed: 24372485]
23. Pang X, Wang H, Zhao XR, Jin WJ. Cryst Eng Comm. 2013; 15:2722–2730.

24. Riley KE, Murray JS, Politzer P, Concha MC, Hobza P. *J Chem Theory Comput.* 2009; 5:155–163. [PubMed: 26609829]
25. Scheiner S. *Cryst Eng Comm.* 2013; 15:3119–3124.
26. Stone AJ. *J Am Chem Soc.* 2013; 135:7005–2009. [PubMed: 23581907]
27. Adhikari U, Scheiner S. *Chem Phys Lett.* 2012; 532:31–35.
28. Riley KE, Murray JS, Fanfrlik J, Székely J, Solá RJ, Concha MC, Ramos FM, Politzer P. *J Mol Model.* 2011; 17:3309–3318. [PubMed: 21369930]
29. Riley KE, Murray JS, Fanfrlik J, Székely J, Solá RJ, Concha MC, Ramos FM, Politzer P. *J Mol Model.* 2013; 19:4651–4659. [PubMed: 22643966]
30. Kolář MH, Hostaš J, Hobza P. *Phys Chem Chem Phys.* 2014; 16:9987–9996. [PubMed: 24477636]
31. Sedlak R, Kolář MH, Hobza P. *J Chem Theory Comput.* 2015; 11:4727–4732. [PubMed: 26574261]
32. Riley KE, Pitonák M, Jurecka P, Hobza P. *Chem Rev.* 2010; 110:5023–5063. [PubMed: 20486691]
33. Jeziorski B, Moszynski R, Szalewicz K. *Chem Rev.* 1994; 94:1887–1930.
34. Parker TM, Burns LA, Parrish RM, Ryno AG, Sherrill CD. *J Chem Phys.* 2014; 140:094106. [PubMed: 24606352]
35. Hohenstein EG, Sherrill CD. *WIREs: Comput Mol Sci.* 2012; 2:304–326.
36. MOLPRO is a package of ab initio programs written by H.-H. Werner, P. J. Knowles, G. Knizia, F. R. Manby, M. Schuetz, P. Celani, W. Gyorffy, D. Kats, T. Korona, R. Lindh A. Mitrushenkov, G. Ruhut, K. R. Shamasundar, T. B. Adler, R. D. Amos, A. Bernhardsson, A. Berning, D. L. Cooper, M. J. O. Deegan, A. J. Dobbyn, F. Eckert, E. Goll, C. Hampel, A. Hesselmann, G. Hetzer, T. Hrenar, G. Jansen, C. Koepl, Y. Liu, A. W. Lloyd, R. A. Mata, A. J. May, S. J. McNicholas, W. Meyer, M. E. Mura, A. Nicklass, D. P. O'Neill, P. Palmieri, D. Peng, K. Pflueger, R. Pitzer, M. Reiher, T. Shiozaki, H. Stoll, A. J. Stone, R. Tarroni, T. Thorsteinsson, M. Wang.
37. Turney JM, Simmonett AC, Parrish RM, Hohenstein EG, Evangelista F, Fermann JT, Mintz BJ, Burns LA, Wilke JJ, Abrams ML, Russ NJ, Leininger ML, Janssen CL, Seidl ET, Allen WD, Schaefer HF, King RA, Valeev EF, Sherrill CD, Crawford TD. *WIREs Comput Mol Sci.* 2012; 2:556.
38. Shao Y, Molnar LF, Jung Y, Kussmann J, Ochsenfeld C, Brown ST, Gilbert ATB, Slipchenko LV, Levchenko SV, O'Neill DP, DiStasio RA Jr, Lochan RC, Wang T, Beran GJO, Besley NA, Herbert JM, Lin CY, Van Voorhis T, Chien SH, Sodt A, Steele RP, Rassolov VA, Maslen PE, Korambath PP, Adamson RD, Austin B, Baker J, Byrd EFC, Dachsel H, Doerksen RJ, Dreuw A, Dunietz BD, Dutoi AD, Furlani TR, Gwaltney SR, Heyden A, Hirata S, Hsu C-P, Kedziora G, Khalliulin RZ, Klunzinger P, Lee AM, Lee MS, Liang WZ, Lotan I, Nair N, Peters B, Proynov EI, Pieniazek PA, Rhee YM, Ritchie J, Rosta E, Sherrill CD, Simmonett AC, Subotnik JE, Woodcock HL III, Zhang W, Bell AT, Chakraborty AK, Chipman DM, Keil FJ, Warshel A, Hehre WJ, Schaefer HF, Kong J, Krylov AI, Gill PMW, Head-Gordon M. *Phys Chem Chem Phys.* 2006; 8:3172. [PubMed: 16902710]

Figure 1.
Degrees of freedom for R-Br... π complexes considered in this work.

Figure 2. Electrostatic potential maps of benzene (top) and R-X... π donors (bottom); HBr (left), HCCBr (middle), and NCBBr (right). Blue: positive potential, green: neutral, red: negative.

Figure 3.

A: CCSD(T) (dotted) and SAPT (solid) potential energy curves (along R_1 coordinate) for all $R\text{-Br}\dots\pi$ complexes (C_{6v} geometries). Blue: $\text{HBr}\dots\text{C}_6\text{H}_6$; red: $\text{HCCBr}\dots\text{C}_6\text{H}_6$; green: $\text{NCBr}\dots\text{C}_6\text{H}_6$. **B:** SAPT potential energy curves. solid: $\text{HBr}\dots\text{C}_6\text{H}_6$; dotted: $\text{HCCBr}\dots\text{C}_6\text{H}_6$; dashes and dots: $\text{NCBr}\dots\text{C}_6\text{H}_6$. Exchange: red; induction: purple; electrostatic: blue; dispersion: green;

Figure 4.

A: CCSD(T) (dotted) and SAPT (solid) potential energy curves for tilting of R-Br... π donors above benzene plane ($a(\text{R-Br}\dots\pi)$) at C_{6v} minimum (R_{1eq}). Blue: $\text{HBr}\dots\text{C}_6\text{H}_6$; red: $\text{HCCBr}\dots\text{C}_6\text{H}_6$; green: $\text{NCBr}\dots\text{C}_6\text{H}_6$. **B:** SAPT potential energy curves as function of $a(\text{R-Br}\dots\pi)$ at R_1 separation of $3.4\text{\AA}$. solid: $\text{HBr}\dots\text{C}_6\text{H}_6$; dotted: $\text{HCCBr}\dots\text{C}_6\text{H}_6$; dashes and dots: $\text{NCBr}\dots\text{C}_6\text{H}_6$. Exchange: red; induction: purple; electrostatic: blue; dispersion: green; E: black.

Figure 5.

A: CCSD(T) (dotted) and SAPT (solid) potential energy curves for shifting of R-Br... π donors above benzene plane (R2) at C_{6v} minimum (R_{1eq}). Blue: HBr... C_6H_6 ; red: HCCBr... C_6H_6 ; green: NCB... C_6H_6 . **B:** SAPT potential energy curves as function of R2 at R1 separation of 3.4 Å. solid: HBr... C_6H_6 ; dotted: HCCBr... C_6H_6 ; dashes and dots: NCB... C_6H_6 . Exchange: red; induction: purple; electrostatic: blue; dispersion: green; E: black.