

Can Lone Pairs Bind to a π System? The Water···Hexafluorobenzene Interaction

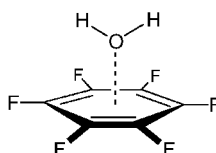
Justin P. Gallivan and Dennis A. Dougherty*

Arnold and Mabel Beckman Laboratories of Chemical Synthesis, Division of Chemistry
and Chemical Engineering, 164-30, California Institute of Technology,
Pasadena, California 91125

dad@igor.caltech.edu

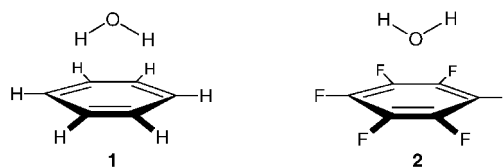
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ABSTRACT



Ab initio calculations reveal a significant binding interaction between water and hexafluorobenzene in a geometry that points the oxygen lone pairs directly into the face of the π system. The geometry is as anticipated from electrostatic arguments emphasizing the substantial quadrupole moment of the aromatic. A second, off-axis geometry is also found which is also consistent with a substantial electrostatic interaction.

The past decade has seen a substantial rethinking of the bimolecular interactions between aromatic rings and other small molecules. Binding motifs with large electrostatic components such as the cation- π ,¹ amino-aromatic,² and polar- π interactions³ produce a new view of benzene as a polar molecule. Benzene has a large, permanent quadrupole moment,^{4,5} such that there is substantial negative electrostatic potential above and below the plane of the ring, and a belt of positive potential around the edge. Ionic and polar species interact with this moment as anticipated by purely electrostatic arguments. A prototype system is water···benzene. Water binds to benzene with a calculated 1.8 kcal/mol of binding energy in the geometry (1) expected from electrostatic arguments.⁶



It has long been recognized that hexafluorobenzene has a quadrupole moment that is comparable in magnitude but opposite in sign to that of benzene—positive regions become negative and negative positive.⁵ This leads, for example, to the very favorable stacking interaction between aryl and perfluoroaryl rings.^{5,7,8} Similar reasoning suggests that water should also bind to hexafluorobenzene but in the geometry of 2 with the water dipole moment reversed relative to the water···benzene interaction. While quite reasonable from an electrostatic viewpoint, from another perspective this interaction is somewhat counterintuitive. It suggests that a π electron system should be attracted to a set of lone pair electrons. One might expect significant electron–electron repulsions that are not present for water···benzene. As such, the water···hexafluorobenzene interaction pushes the limits of

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Table 1. Results of ab Initio Calculations

theory	structure 3		structure 4				
	r (Å)	binding energy ^a	r (Å)	θ	ϕ	H...F (Å)	binding energy ^a
HF/6-31G**	3.22	2.49	3.96	41.8	36.9	2.61	2.95
CP-HF/6-31G**	3.50	1.67	nd ^b	nd	nd	nd	nd
MP2(full)/6-31G**	2.94	3.90	3.77	42.5	48.5	2.33	3.77
CP-MP2(full)/6-31G**	3.20	2.11	4.05	45.0	14.9	2.93	1.69
B3LYP/6-31G**	3.08	2.43	3.95	39.6	60.7	2.30	4.32

^a kcal/mol. ^b nd = not determined.

electrostatic arguments in rationalizing noncovalent binding interactions to aromatics.

We now report ab initio molecular orbital calculations which indicate that water binds to hexafluorobenzene in the anticipated geometry and that the magnitude of the interaction (2.1 kcal/mol) is quite comparable to the water...benzene interaction (1.8 kcal/mol). Thus, there appears to be no substantial penalty for pointing oxygen lone pairs into a π electron system. The water interaction with hexafluorobenzene is thus consistent with those of other small polar molecules such as HF or HCN.⁹ In addition, we have found a second water...hexafluorobenzene minimum (binding energy = 1.7 kcal/mol), with the water located substantially off the C_6 axis, but still in a position that can be rationalized using electrostatics.

Table 1 summarizes the results of calculations on water interacting with hexafluorobenzene. Calculations on non-covalent systems can be challenging. Our goal here is not to present the highest level of theory imaginable for this system. Rather, we employ a competent level of theory that has been shown⁶ to handle the water...benzene system well, as our major goal is to compare structures **1** and **2**. While more advanced theory may change some quantitative aspects of our results, we are confident that no qualitative conclusions will change. The highest level of theory involved MP2/6-31G** calculations with counterpoise (CP) corrections for basis set superposition error (BSSE). As in our previous study of benzene...hexafluorobenzene,⁸ we find that BSSE strongly affects the interaction distance between water and the aromatic (but no other geometrical parameters), and so this distance has been optimized with the CP correction. This level of theory is equivalent to that applied previously to water...benzene,⁶ making direct comparisons meaningful.

The global minimum for water...hexafluorobenzene (**3**, Figure 1) is as anticipated from electrostatic arguments, and the binding energy is quite comparable to that for water...benzene. There appear to be no adverse electron-electron repulsions. Not surprisingly, the potential energy surface is quite flat in this region, and the binding energy in the eclipsed geometry shown differs by less than 1 cal/mol

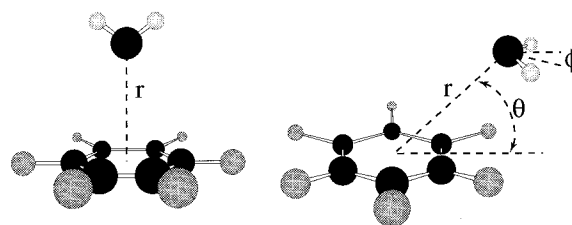


Figure 1. CP-MP2 minima for structures **3** (left) and **4** (right). See Table 1 for values of r , θ , and ϕ .

from the 15° and 30° staggered geometries (CP-MP2(full)/6-31G** level).

Optimization starting from an electrostatically unfavorable geometry with an O–H bond located on the C_6 axis and the hydrogen pointed toward the face of the ring led to a second minimum (**4**) in which the water has moved well off-axis. This structure is calculated to be only slightly less stable than the on-axis geometry (–1.7 vs –2.1 kcal/mol). Rather than a symmetrical alignment of molecular moments (dipole/quadrupole), this geometry represents a favorable alignment of local O–H and C–F bond dipoles and so presumably still has a substantial electrostatic component. Efforts to find an analogous minimum for water...benzene were not successful—all starting geometries led to structures similar to that previously reported for water...benzene.

Given the increasing interest in DFT methods, we have also evaluated structures **3** and **4** using the Becke3LYP density functional and the 6-31G** basis set. Since no counterpoise corrections were applied, the most appropriate comparison is to the MP2 results. In our earlier study of benzene...hexafluorobenzene,⁸ DFT performed poorly, being comparable to simple HF calculations. However, for water...hexafluorobenzene, DFT produces good results for the global minimum **3**, producing values that are in acceptable agreement with the MP2 results and are actually quite close to the full CP-MP2 results (Table 1). While CP-MP2 predicts a significant preference for **3**, DFT finds the off-axis structure **4** to be more stable. Both the DFT and the MP2 structures have a much larger value of Φ , the tilt angle of the water molecule, than the CP-MP2 structure. This tilting brings the water hydrogens very close to the fluorines, well

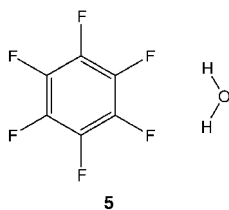
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inside van der Waals contact, indicative of a hydrogen bond. Dunitz has concluded that hydrogen bonds to fluorine are not energetically significant,¹⁰ but it appears that both DFT and MP2 consider such an interaction to be important. It is clear that BSSE will be most important when noncovalent contacts to fluorine are involved, because of the large demands fluorine puts on its basis set. Thus, it is perhaps not surprising that the CP corrections are most significant for **4**—note that there are no close contacts to fluorine in the on-axis structure **3**. For these reasons we consider the CP-MP2 level to be the best for comparisons of the two structures.

The results for **4** suggest that a fully in-plane structure (**5**) might be favorable. However, at the HF/6-31G** level such a structure is in fact a transition state separating two equivalent forms of **4**.



These results further illustrate the power of electrostatic reasoning in studies of noncovalent interactions involving aromatics. In the absence of such effects, one would never predict a stabilizing interaction for a geometry that points oxygen lone pairs directly into the face of a π system as observed here. As always, other effects related to polarizability and dispersion interactions no doubt contribute to the

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binding energy, but all the structures discussed here can be accurately anticipated on the basis of electrostatics alone. These results provide further support for the idea first put forth by Reisse⁴ that aromatics such as benzene and hexafluorobenzene are correctly thought of as polar molecules and clearly underscore the importance of electrostatic reasoning in evaluating novel intermolecular interactions.¹¹

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(11) All calculations were performed using Gaussian 94 Rev. D.3.¹² Geometry optimizations were first performed at the HF level using the 6-31G** basis set. Frequency calculations performed on fully optimized structures at the HF level produced no negative frequencies (except structure **5**), indicating that the geometries were true minima. Using the Hartree–Fock frequency calculations, we estimate the zero point energy (ZPE) correction to be +0.58 kcal/mol for **3** and +0.89 kcal/mol for **4** using the frequency scaling factor of 0.8992 suggested by Scott and Radom.¹³ These results are not included in Table 1. Counterpoise-corrected optimizations (designated CP) were performed using the method of Bernardi and Boys.¹⁴ First, the component molecules, water and hexafluorobenzene, were individually optimized at either the HF/6-31G** level or the MP2(full)/6-31G** level. The internal coordinates of the optimized monomers were kept fixed, and the complexes were optimized by scanning the potential energy surface at several points. CP corrections were performed at each point, and this corrected binding energy was minimized. The results of these calculations are designated CP-HF/6-31G** or CP-MP2(full)/6-31G**.

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