J. Phys. Chem. A **2006,** *110,* 12705−12710

Arene−Cation Interactions of Positive Quadrupole Moment Aromatics and Arene−Anion Interactions of Negative Quadrupole Moment Aromatics

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Received: August 10, 2006

Intermolecular interactions involving aromatic π-electron density are widely believed to be governed by the aromatic molecular quadrupole moment, Θ_{zz}. Arene−cation binding is believed to occur primarily with negative Θ_{zz} aromatics, and arene−anion binding is believed to occur largely with positive Θ_{zz} aromatics. We have performed quantum mechanical computations that show the cation binding of positive Θ_{zz} aromatics and the anion binding of negative Θ_{zz} aromatics is quite common in the gas phase. The π-electron density of hexafluorobenzene, the prototypical positive Θ_{zz} aromatic (experimental $\Theta_{zz} = +9.5 \pm 0.5$ DÅ), has a Li^+ binding enthalpy of -4.37 kcal/mol at the MP2(full)/6-311G** level of theory. The RHF/6-311G** calculated Θ_{zz} value of 1,4-dicyanobenzene is $+11.81$ DÅ, yet it has an MP2(full)/6-311G** Li^+ binding enthalpy of -12.65 kcal/mol and a Na^+ binding enthalpy of -3.72 kcal/mol. The π-electron density of benzene, the prototypical negative Θ_{zz} aromatic (experimental $\Theta_{zz} = -8.7 \pm 0.5$ DÅ), has a F^- binding enthalpy of -5.51 kcal/mol. The RHF/6-311G** calculated Θ_{zz} of $C_6H_2I_4$ is -10.45 DÅ, yet it has an MP2(full)/6-311++G** calculated F^- binding enthalpy of -20.13 kcal/mol. Our results show that as the aromatic Θ_{zz} value increases the cation binding enthalpy decreases; a plot of cation binding enthalpies versus aromatic Θ_{zz} gives a line of best of fit with $R^2 = 0.778$. No such correlation exists between the aromatic Θ_{zz} value and the anion binding enthalpy; the line of best fit has $R^2 = 0.297$. These results are discussed in terms of electrostatic and polarizability contributions to the overall binding enthalpies.

Introduction

Noncovalent interactions involving aromatic π-electron density[1] are important in organic reaction development[2] and enzyme−substrate recognition.[3] The cation-π interaction of aromatics is ubiquitous in chemistry, and recent work describes the importance of the interaction in ion channels,[4] protein folding,[5] acetylcholine esterase activity,[6] galectin protein function,[7] and small-molecule organic reaction mechanisms.[8] The anion-π interaction has not been investigated for as long as the cation-π interaction; however, there is an impressive body of computational works detailing anion−arene interactions with electron-poor aromatics. These studies can generally be divided into work where the aromatic is a substituted benzene[9] and work where electron-poor heteroaromatics such as triazines are employed.[9a−c,10] Experimental studies have begun to show solid-state examples of anion-π interactions involving electron-poor aromatics,[11] and very recently an NMR spectroscopic study suggested the presence of an anion-π interaction in solution,[12] again where the π-system is an electron-poor aromatic.[13]

The cation binding of aromatic π-electron density (cation-π interaction) has primarily been studied using electron-rich aromatics with a negative molecular quadrupole moment, Θ_{zz},[1] and anion binding (anion-π interaction) has largely been studied with electron-poor, positive Θ_{zz} aromatics.[9] Cation-π interactions involving positive Θ_{zz} aromatics and anion-π interactions with negative Θ_{zz} aromatics have generally been assumed to be repulsive. The rationale for neglecting the latter two interactions, and leaving half of all possible aromatic cation-π and anion-π interactions uninvestigated, is based on a first-principles approach. The measurable Θ_{zz} for C_6H_6 is -8.7 ± 0.5 DÅ,[14] and the common explanation for the negative value is the $\{- + -\}$ electron density distribution one encounters when going from one π-cloud, through the hydrocarbon framework, onto the other π-cloud (the *z*-axis in Figure 1). The cation-binding ability of benzene, or any negative Θ_{zz} aromatic, has been explained as an electrostatic attraction between the cation and one of the negative ends of the aromatic quadrupole moment (type **A** interaction, Figure 1). The Θ_{zz} value of C_6F_6 is $+9.5 \pm 0.5$ DÅ,[14] and this is commonly used to describe the electron density distribution along the *z*-axis in C_6F_6 as $\{+ - +\}$. The anion-binding ability of positive Θ_{zz} aromatics is then explained as an electrostatic attraction between the anion and one of the positive ends of the aromatic Θ_{zz} (type **B** interaction, Figure 1).

More recently, the importance of aromatic π-electron density polarizability has been demonstrated for type **A**[15] and **B**[9c,e] interactions. In both cases the energy due to the polarizability of the aromatic π-electron density and the energy due to electrostatics were the major contributors to the total binding energy. The effect of aromatic π-electron density polarizability in aromatic binding is depicted pictorially in Figure 2, eqs **1** and **2**, and this offers a modification of the first principles approach illustrated in Figure 1. Inspection of eqs **1** and **2** leads to the hypothesis that if π-electron density polarizability is an important factor in type **A** and **B** interactions, then there is every reason to expect positive Θ_{zz} aromatics will bind cations (type **C** interactions, Figure 2) and negative Θ_{zz} aromatics will bind anions (type **D** interactions, Figure 2) as depicted by eqs **3** and **4** (Figure 2). Even though the importance of π-electron density polarizability in interactions involving aromatics is well estab-

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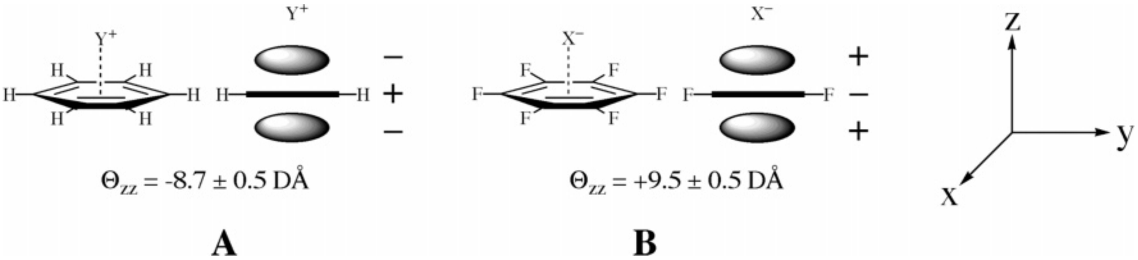

Figure 1. Cation binding of a negative Θ_{zz} aromatic (benzene), type **A** interaction, and anion binding of a positive Θ_{zz} aromatic (hexafluorobenzene), type **B** interaction.

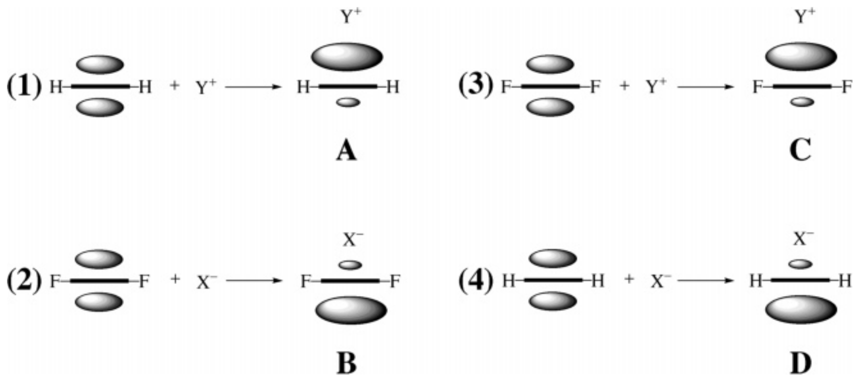

Figure 2. Aromatic π-electron density polarizability in types **A**, **B**, **C**, and **D** interactions.

lished, type **C** and **D** interactions are still treated as exceptions to the rule. Three aromatics with small positive Θ_{zz} values (1,3,5-trifluorobenzene: 0.57 DÅ; *s*-triazine: 0.90 DÅ; 2,5-dichloropyrazine: 1.47 DÅ) were recently shown to bind Na^+ (type **C** interactions), but the researchers attributed this to the negligible Θ_{zz} values.[16] Another recent study demonstrated that the aromatic 1,4,5,8,9,12-hexaazatriphenylene, with $\Theta_{zz} = -8.53$ DÅ, binds Br^- (type **D** interaction); however, the authors explicitly note the binding occurs despite the aromatic having a negative quadrupole moment.[9b]

Here we report the results of a quantum mechanical study that expands on the previously developed theories and shows that, in the gas-phase, the π-electron density of a large number of positive Θ_{zz} aromatics will bind cations, even in cases where the aromatics have large positive Θ_{zz} values. We will also show that the π-electron density of a large number of negative Θ_{zz} aromatics binds anions, even in cases where the aromatics have large negative Θ_{zz} values. The relationships between aromatic-cation binding enthalpies and the aromatic molecular quadrupole moment and between aromatic-anion binding enthalpies and the aromatic polarizability are also discussed.

Computational Methods

For the purpose of determining the aromatic quadrupole moments, Θ_{zz}, all aromatics were optimized and characterized via frequency calculations at the RHF/6-311G** level of theory. This method has been shown to give excellent agreement with experiment,[17] and this is borne out in our calculations; the experimental quadrupole moments for benzene and hexafluorobenzene are -8.7 ± 0.5 DÅ and $+9.5 \pm 0.5$ DÅ,[14] respectively, and the RHF/6-311G** calculated values are -8.76 DÅ and $+10.06$ DÅ. For the purpose of determining aromatic-cation binding enthalpies, the aromatics were reoptimized at the MP2(full)/6-311G** level of theory along with the Li^+ and Na^+ cations and the aromatic-cation complexes. This level of theory agrees very well with experiment; the calculated $C_6H_6-Na^+$ binding enthalpy at this level of theory is $\Delta H_{298} = -24.51$ kcal/mol, and this is just outside the standard deviation for the experimentally determined value ($\Delta H_{298} = -22.13 \pm 1.39$ kcal/mol).[18] For the purpose of determining aromatic-anion binding enthalpies, the aromatics were reoptimized at the MP2(full)/6-311++G** level of theory along with the F^- anion and the aromatic-arene complexes. All of the MP2(full)/6-311G** and MP2(full)/6-311++G** calculated structures were characterized via frequency calculations and the arene−cation and arene−anion binding energies were corrected for basis set superposition error (BSSE) using the counter-poise method.[19] The basis sets noted above are not parametrized for iodine, and thus for calculations involving iodo-substituted aromatics the MIDI! basis set was employed for the iodine atoms. To comment on the energy due to electrostatics and the energy due to polarizability, Morokuma−Kitaura decomposition calculations[20] were performed on selected cation- and anion-complexes. These calculations were performed at the RHF/6-311G level of theory.[21] All calculations were performed using Gaussian03[22] except for the Morokuma−Kitaura decomposition calculations, which used GAMESS.[23]

Results and Discussion

The Li^+ and Na^+ complexes of the positive Θ_{zz} aromatics in Table 1 were calculated in C_{6v}, C_{4v}, and C_{2v} symmetry, depending on the symmetry of the aromatic, and the absence of imaginary frequencies confirmed the structures were minima. The data unequivocally illustrates that positive Θ_{zz} aromatics bind cations (Table 1). The Θ_{zz} value of 1,3,5-tricyanobenzene is $+21.12$ DÅ, yet it has a Li^+ binding enthalpy of -4.12 kcal/mol. The Na^+ binding enthalpy of 1,4-dicyanobenzene is -3.72 kcal/mol even though the aromatic has a Θ_{zz} value of $+11.81$ DÅ. It is not until the Θ_{zz} value of the aromatic approaches 30 DÅ that the arene−Li^+ complex becomes repulsive, whereas the arene−Na^+ complex becomes repulsive at about 20 DÅ. It is worth noting that hexafluorobenzene, the prototypical positive Θ_{zz} aromatic, has a Li^+ binding enthalpy of -4.37 kcal/mol.

An additional, but not unexpected, result of our study is the relationship between the aromatic Θ_{zz} value of positive Θ_{zz} aromatics and the cation binding enthalpies (Figures 3 and 4).

TABLE 1: MP2(full)/6-311G Calculated Li^+ and Na^+ Binding Enthalpies of Positive Θ_{zz} Aromatics**[a]

		Li^+ binding (kcal/mol)		Na^+ binding (kcal/mol)	
aromatic	Θ_{zz} (DÅ)	$\Delta E_{0,BSSE}$	$\Delta H_{298,BSSE}$	$\Delta E_{0,BSSE}$	$\Delta H_{298,BSSE}$
$C_6F_4I_2$	+0.51	−16.47	−15.45	−6.61	−5.82
$C_6H_3F_3$	+0.69	−19.89	−18.55	−10.30	−9.27
$C_6F_2Cl_4$	+2.96	−12.71	−11.55	−3.97	−3.08
$C_6H_2F_4$	+4.08	−14.97	−13.73	−5.68	−4.71
$C_6F_4Br_2$	+4.35	−11.28	−10.20	−3.01	−2.17
$C_6F_4Cl_2$	+6.49	−9.35	−8.21	−1.41	−0.54
C_6F_6	+10.06	−5.56	−4.37	+1.41	+2.31
$C_6H_4(CN)_2$	+11.81	−13.88	−12.65	−4.61	−3.72
$C_6H_3(CN)_3$	+21.12	−5.02	−4.12	+2.13	+2.78
$C_6H_2(CN)_4$	+27.84	+2.54	+3.36	+7.59	+8.13

[a] The Θ_{zz} values were calculated at the RHF/6-311G** level of theory.

A plot of the Li^+ ΔH_{298} binding enthalpies versus Θ_{zz} gives a good linear correlation ($R^2 = 0.778$, Figure 3a), and this is significantly improved when the aromatics that contain CN groups are separated from the aromatics with no CN substituents ($R^2 = 0.997$ and $R^2 = 0.888$, respectively, Figure 3b). Figure 4 shows almost identical trends for Na^+ complexes of the positive Θ_{zz} aromatics. These results are in agreement with work reported by Dougherty and co-workers on the cation binding of negative Θ_{zz} aromatics where they showed the total cation binding energy (E_{tot}) of the aromatic is directly related to the electrostatic contribution (E_{ele}) to the overall binding.[24] The relationship between our results and Dougherty's results is not surprising since Θ_{zz} describes the electrostatic potential; however, it is worth noting that we are observing this correlation for positive Θ_{zz} aromatics, whereas Dougherty's work demonstrated the correlation for negative Θ_{zz} aromatics.

We also calculated the F^- complexes of the negative Θ_{zz} aromatics in Table 2 in C_{6v}, C_{4v}, and C_{2v} symmetry, depending on the symmetry of the aromatic. Unlike the case of the arene−cation complexes, the frequency calculations revealed 2 or 3 imaginary frequencies for each arene−anion complex. Deya and co-workers found that the C_{6v} symmetric $C_6F_6{-}F^-$ complex also had two imaginary frequencies.[9g] Upon relaxing the symmetry constraints they determined a local minimum structure that corresponded to the F^- attacking an aromatic C-atom in S_NAr fashion. We relaxed the symmetry constraint on the $C_6H_4F_2{-}F^-$ complex and obtained the same result; the structure of the local minimum corresponded to S_NAr attack of the F^- on one of the C−F carbon atoms. Even though the fluoride complexes in Table 2 are not minima, the fact that negative Θ_{zz} aromatics bind anions is still significant, dispelling the idea that the π-electron density of negative Θ_{zz} aromatics only binds cations. For instance, the Θ_{zz} of $C_6H_2Br_4$ is −4.32 DÅ, yet it has a F^- binding enthalpy of −11.18 kcal/mol.

In contrast to the cation binding of positive Θ_{zz} aromatics, there is no correlation between the F^- ΔH_{298} binding enthalpy of negative Θ_{zz} aromatics and the aromatic Θ_{zz} value. When the F^- ΔH_{298} binding enthalpy is plotted against the Θ_{zz} of negative Θ_{zz} aromatics, the line of best fit gives an $R^2 = 0.297$ (Figure 5). Thus, Θ_{zz} does not serve as a predictor for the anion binding of negative Θ_{zz} aromatics.

As we already noted, Dougherty showed that the electrostatic component (E_{ele}) of the total binding energy is all that varies in the Na^+-binding of a series of negative Θ_{zz} aromatics.[24] In a broader sense, Dougherty has shown conclusively and elegantly that the electrostatic component of the arene−cation binding energy is all that needs to be considered when predicting the trend in cation-binding for negative Θ_{zz} aromatics.[1c] An important part of Dougherty's work was demonstrating that as the aromatic Θ_{zz} value approached zero, E_{ele} becomes negligible and other factors, such as π-electron density polarizability, account for the cation-binding capability of certain aromatics.[24] As part of these studies Dougherty showed that the binding energy not due to electrostatics was constant, about 12 kcal/mol.[24] Since the molecular quadrupole moment describes the electron density distribution of the aromatic, and because we show here a direct correlation between the cation binding of positive Θ_{zz} aromatics and the aromatic Θ_{zz} value, it is reasonable to suggest that the variation in binding energy of the Li^+- and Na^+-complexes of positive Θ_{zz} aromatics is also primarily due to E_{ele}. Taken with Dougherty's results, this would mean the cation-binding of all aromatics, those with positive and negative Θ_{zz} values, is governed by electrostatics. We performed Morokuma−Kitaura (MK) decomposition calculations for three of the cation−arene complexes in Table 1, and for benzene, to address this issue, and the results are shown in Table 3. The results show a pattern similar to the results reported by Dougherty for negative Θ_{zz} aromatics. The binding energy due to polarizability, E_{pol}, is constant, and the variation in total binding energy is due to the variation in E_{ele}. The absolute values for the total binding energies ($E_{tot,MK}$), the E_{ele} values, and the E_{pol} values calculated using the MK method should be considered with skepticism, since it is not possible to employ electron correlation when performing MK calculations; however, the trends do allow for insights. It is noteworthy that the average E_{pol} for the four arene−Na^+ in Table 3 is −10.5 kcal/mol. This is close to the −12 kcal/mol energy constant that Dougherty ascribed to all nonelectrostatic terms,[24] and this suggests the binding energy not due to electrostatics for cation−arene complexes of positive and negative Θ_{zz} aromatics can primarily be attributed to the binding energy due to polarizability. It is worth noting the electrostatic component of the binding energy for positive Θ_{zz} aromatics is repulsive, yet the E_{ele} term still accounts for the variation in the total binding energy, just as Dougherty illustrated for negative Θ_{zz} aromatics.[24]

Drawing from what Dougherty elucidated about cation binding of negative Θ_{zz} aromatics and what we presented above about the cation binding of positive Θ_{zz} aromatics, the lack of correlation between the anion binding of negative Θ_{zz} aromatics and the aromatic Θ_{zz} value leads to the prediction that E_{ele} does not vary for the anion binding of negative Θ_{zz} aromatics. Furthermore, since the anion binding energy of negative Θ_{zz} aromatics does vary for differently substituted aromatics, we expect another term in the total anion binding energy to vary. The MK decomposition calculations on the F^- complexes of the negative Θ_{zz} aromatics in Table 4 show this pair of predictions is half right. The E_{ele} term does in fact vary for differently substituted aromatics, contradicting the first prediction; however, the E_{pol} term also varies, validating the second prediction. The fact that E_{ele} varies, yet there is no correlation between the anion binding enthalpy of negative Θ_{zz} aromatics and the aromatic Θ_{zz} value, can be reconciled since E_{pol} contributes more to the overall binding than E_{ele}. The MK calculations show that the E_{pol} value is completely due to the polarizability of the aromatic, and thus it appears the aromatic ring polarizability may be responsible for the variation in the anion binding capability of negative Θ_{zz} aromatics.

An important question arises with regard to the role of aromatic ring polarizability in the anion binding of negative Θ_{zz} aromatics: what part of the aromatic ring is polarized. The assumption might be that the aromatic π-electron density is polarized; however, closer inspection of the anion binding

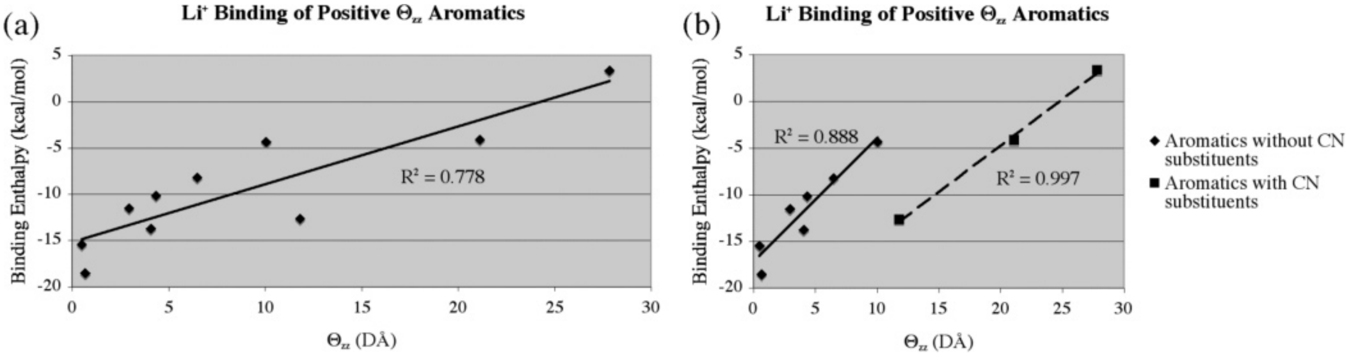

Figure 3. Plot (a): Li^+ ΔH_{298} binding enthalpy of positive Θ_{zz} aromatics versus aromatic Θ_{zz}. Plot (b): aromatics separated based on the presence of cyano groups.

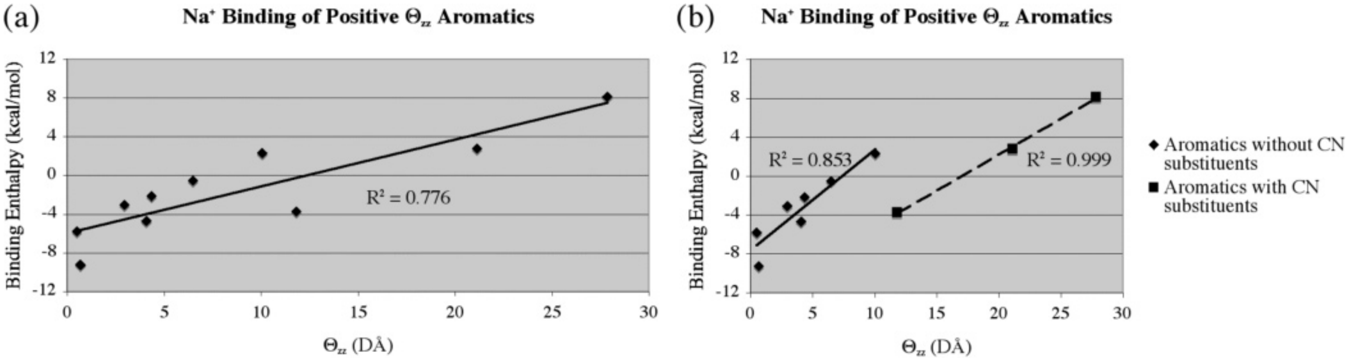

Figure 4. Plot (a): Na^+ ΔH_{298} binding enthalpy of positive Θ_{zz} aromatics versus aromatic Θ_{zz}. Plot (b): aromatics separated based on the presence of cyano groups.

TABLE 2: MP2(full)/6-311++G Calculated F^- Binding Enthalpies of Negative Θ_{zz} Aromatics**[a]

		F^- binding (kcal/mol)	
aromatic	Θ_{zz} (DÅ)	$\Delta E_{0,BSSE}$	$\Delta H_{298,BSSE}$
$C_6H_3Cl_3$	−1.76	−7.91	−7.05
$C_6H_4F_2$	−2.17	−4.29	−4.95
$C_6H_4Cl_2$	−3.47	−5.31	−5.79
$C_6H_2Br_4$	−4.32	−10.91	−11.18
$C_6H_4Br_2$	−4.78	−5.50	−5.90
$C_6H_4I_2$	−7.73	−3.26	−4.09
$C_6H_3I_3$	−8.39	−5.92	−5.30
C_6H_6	−8.76	2.56	−0.14

[a] The Θ_{zz} values were calculated at the RHF/6-311G** level of theory.

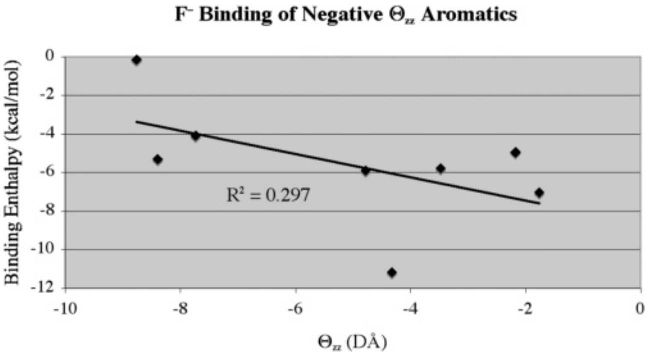

Figure 5. F^- ΔH_{298} binding enthalpy of negative Θ_{zz} aromatics versus aromatic Θ_{zz}.

enthalpies in Table 2 suggests otherwise. It appears anion-binding increases with greater halogen substitution and with substitution of more polarizable halogen atoms. For instance, the F^--binding of $C_6H_4Br_2$ and $C_6H_2Br_4$ are −5.90 and −11.18 kcal/mol and the F^- binding of $C_6H_4F_2$, $C_6H_4Cl_2$, and $C_6H_4Br_2$ are −4.95, −5.79, and −5.90 kcal/mol, respectively. The F^- binding of $C_6H_4I_2$ does not fit into this trend; however, a different basis set was used for iodine than for the rest of the elements (MIDI! instead of 6-311++G**), and this may be the reason for the discrepancy. To determine the importance of halogen substitution in the anion binding of negative Θ_{zz} aromatics, and possible lack of importance of π-electron polarizability, we calculated single point energies for the F^- binding of H_2, F_2, Cl_2, Br_2, and I_2 using the $F^-{-}X$ bond distance (d) and the $F^-{-}X{-}X$ bond angle (α) from the optimized F^-−arene complexes. (X = hydrogen atoms or halogen atoms)

TABLE 3: Morokuma−Kitaura Decomposition Calculations for Aromatics Complexed with Na^+[a]

aromatic	Θ_{zz} (DÅ)	E_{ele}	E_{pol}	$E_{tot,MK}$
$C_6H_3F_3$	0.69	2.66	−10.61	−3.18
$C_6H_2F_4$	4.08	8.49	−10.17	2.10
C_6F_6	10.06	19.88	−9.23	12.40
C_6H_6	−8.76	−18.06	−12.18	−21.68

[a] The Θ_{zz} values were calculated at the RHF/6-311G** level of theory. The binding energy due to electrostatics (E_{ele}), the binding energy due to polarizability (E_{pol}), and the total binding energy $E_{tot,MK}$ were calculated at the RHF/6-311G level of theory using the Morokuma−Kitaura decomposition method. All energies are in kcal/mol.

TABLE 4: Morokuma−Kitaura Decomposition Calculations for Negative Θ_{zz} Aromatics Complexed with F^-[a]

aromatic	Θ_{zz} (DÅ)	E_{ele}	E_{pol}	$E_{tot,MK}$
$C_6H_3Cl_3$	−1.76	−4.88	−9.22	−15.19
$C_6H_4F_2$	−2.17	−0.49	−6.54	−9.52
$C_6H_4Cl_2$	−3.47	0.28	−7.96	−9.61
C_6H_6	−8.76	9.28	−3.95	3.35

[a] The Θ_{zz} values were calculated at the RHF/6-311G** level of theory. The binding energy due to electrostatics (E_{ele}), the binding energy due to polarizability (E_{pol}), and the total binding energy $E_{tot,MK}$ were calculated at the RHF/6-311G level of theory using the Morokuma−Kitaura decomposition method. All energies are in kcal/mol.

TABLE 5: MP2(full)/6-311++G Single Point Binding Energies for $F^-{-}X_2$, Where X = H_2, F_2, Cl_2, Br_2, and I_2[a]**

arene	interaction	$\Delta E_{bind,BSSE}$	d (Å)	α (°)	$\Delta E_{pred,BSSE}$	$\Delta H_{298,BSSE}$
$C_6H_3Cl_3$	$F^-{-}H_2$	−0.67	3.45	132.19	−9.65	−7.05
	$F^-{-}Cl_2$	−2.55	3.97	138.62		
$C_6H_4F_2$	$F^-{-}H_2$	−0.51	3.71	131.35	−3.38	−4.95
	$F^-{-}F_2$	−0.67	3.90	133.97		
$C_6H_4Cl_2$	$F^-{-}H_2$	−0.55	3.66	131.90	−6.58	−5.79
	$F^-{-}Cl_2$	−2.20	4.13	138.44		
$C_6H_2Br_4$	$F^-{-}H_2$	−0.64	3.55	133.38	−16.07	−11.18
	$F^-{-}Br_2$	−3.70	4.15	141.45		
$C_6H_4Br_2$	$F^-{-}H_2$	−0.56	3.64	132.10	−8.90	−5.90
	$F^-{-}Br_2$	−3.33	4.23	139.98		
$C_6H_4I_2$	$F^-{-}H_2$	−0.55	3.64	131.69	−10.35	−4.09
	$F^-{-}I_2$	−4.08	4.33	141.27		
$C_6H_3I_3$	$F^-{-}H_2$	−0.60	3.59	132.60	−14.75	−5.30
	$F^-{-}I_2$	−4.32	4.28	142.02		
C_6H_6	$F^-{-}H_2$	−0.29	4.15	127.66	−1.74	−0.14

[a] The F-X bond distances (d) and the $F^-{-}X{-}X$ bond angles (α) are from the optimized F^-−arene complexes. The MIDI! basis set is used for iodine; all other atoms are described by the 6-311++G** basis set. The nature of the d and α values are described in Figure 6. ΔE_{pred} is described by eq 1. The $\Delta H_{298,BSSE}$ values are from Table 2. The ΔE and ΔH values are in kcal/mol.

TABLE 6: MP2(full)/6-311G Single Point Binding Energies for $Li^+{-}X_2$, Where X = H_2, F_2, Cl_2, Br_2, and I_2[a]**

arene	interaction	$\Delta E_{bind,BSSE}$	d (Å)	α (°)	$\Delta E_{pred,BSSE}$	$\Delta H_{298,BSSE}$
$C_6F_4I_2$	$Li^+{-}F_2$	−0.74	3.33	144.71	−7.06	−13.48
	$Li^+{-}I_2$	−2.05	3.97	151.22		
$C_6H_3F_3$	$Li^+{-}F_2$	−0.72	3.35	144.72	−3.51	−18.55
	$Li^+{-}H_2$	−0.45	3.16	142.58		
$C_6F_2Cl_4$	$Li^+{-}F_2$	−0.73	3.35	144.49	−3.55	−11.55
	$Li^+{-}Cl_2$	−0.52	3.68	148.24		
$C_6H_2F_4$	$Li^+{-}F_2$	−0.70	3.36	144.88	−3.67	−13.73
	$Li^+{-}H_2$	−0.44	3.17	142.44		
$C_6F_4Br_2$	$Li^+{-}F_2$	−0.71	3.36	144.47	−4.49	−10.20
	$Li^+{-}Br_2$	−0.83	3.83	149.42		
$C_6F_4Cl_2$	$Li^+{-}F_2$	−0.71	3.36	144.47	−3.86	−8.21
	$Li^+{-}Cl_2$	−0.51	3.70	148.15		
C_6F_6	$Li^+{-}F_2$	−0.78	3.38	141.30	−4.68	−4.37

[a] The $Li^+{-}X$ bond distances (d) and the $Li^+{-}X{-}X$ bond angles (α) are from the optimized Li^+−arene complexes. The MIDI! basis set is used for iodine; all other atoms are described by the 6-311G** basis set. The nature of the d and α values are described in Figure 6. ΔE_{pred} is described by eq 1. The $\Delta H_{298,BSSE}$ values are from Table 1. The ΔE and ΔH values are in kcal/mol.

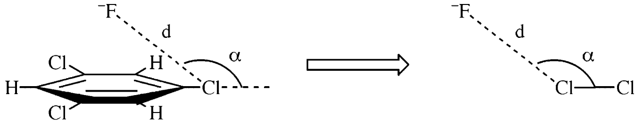

Figure 6. $F^-{-}X_2$ (X = hydrogen atom or halogen atoms) single point energies were calculated taking the $F^-{-}X$ bond distance (d) and the $F^-{-}X{-}X$ bond angle (α) from the optimized F^-−arene complexes.

as shown in Figure 6. The X−X bond distances for H_2, F_2, Cl_2, Br_2, and I_2 were calculated at the MP2(full)/6-311++G** level of theory (the MIDI! basis set was used for I_2). For each F^-−arene complex we determined the $F^-{-}X_2$ binding energy with the appropriate d and α values. Using these binding energies we calculated a predicted binding energy, ΔE_{pred}, based on the total number of $F^-{-}X_2$ interactions.

$$\Delta E_{pred} = 3^*(\Delta E_{bind}\text{ for }F^-{-}H_2) + 3^*(\Delta E_{bind}\text{ for }F^-{-}Cl_2) \tag{1}$$

Equation 1 shows how ΔE_{pred} was calculated for $C_6H_3Cl_3$. Table 5 summarizes the $F^-{-}X_2$ binding energy calculations for all of the arene−anion complexes in Table 2. The most striking result from Table 5 is that ΔE_{pred} is greater than ΔH_{298} in every case but $C_6H_4F_2$. On average, ΔE_{pred} is 164% of ΔH_{298}. This comparison omits C_6H_6 since the F^- binding enthalpy of benzene is close to zero rendering any discussion based on percentages moot. If we also omit the iodo-substituted aromatics, since calculations of these complexes employed the inferior MIDI! basis set for iodine, ΔE_{pred} is 123% of ΔH_{298}. These calculations certainly suggest the anion-binding enthalpies of the F^-−arene complexes are a result of the anion-halogen interactions and not the interaction between the anion and aromatic π-electron density polarizability. To test the veracity of this approach, we repeated the above calculations for the Li^+−arene complexes. The $Li^+{-}X_2$ binding energies, along with ΔE_{pred} and ΔH_{298}, for the Li^+−arene complexes in Table 1, omitting the cyano-substituted aromatics, are collected in Table 6. Employing eq 1 to calculate ΔE_{pred} does not overestimate the ΔH_{298} Li^+−arene binding enthalpies as was the case for the analogous F^- calculations. Instead, ΔE_{pred} is smaller than ΔH_{298} in every case but C_6F_6, and on average ΔE_{pred} is only 46% of ΔH_{298}. At the least, the $F^-{-}X_2$ and $Li^+{-}X_2$ calculated binding energies suggest that the anion-binding enthalpy of halo-substituted aromatics is due to the anion-halogen interaction; however, the cation-binding enthalpy of halo-substituted aromatics is not due to the cation-halogen interaction. Furthermore, the $F^-{-}X_2$ binding energy must be the result of polarizability since the interaction is between an anion and an electronegative atom. If we couple these results with the Morokuma−Kitaura calculations it appears that the anion-binding enthalpy of halo-substituted aromatics is due to the polarizability of the halogen atoms.

Conclusions

The research presented here shows that positive and negative Θ_{zz} aromatics will bind both cations and anions. We have also discussed the relationship between the aromatic Θ_{zz} value and the aromatic-cation binding enthalpy, and our results are in line with the work of Dougherty and researchers on negative Θ_{zz} aromatics. No correlation was found between anion-binding enthalpies and the aromatic Θ_{zz} value for negative Θ_{zz} aromatics. Morokuma−Kitaura decomposition calculations show the major contributor to the overall anion-binding energy is the energy due to the polarizability of the aromatic and this value varies between aromatics. Based on this we believe there may be a correlation between the aromatic-anion binding enthalpy and the aromatic polarizability, a topic that has been briefly looked into by Deya and co-workers,[16b] and we are currently exploring this issue. Interestingly, it may not be the polarizability of the aromatic π-electron density that is responsible for the aromatic-anion binding but rather it may be the polarizability of the aromatic substituents. The results showing anion binding by electron-rich, negative Θ_{zz} aromatics are particularly noteworthy with respect to experimental efforts. All of the experimental work on these interactions employ electron-poor, positive Θ_{zz} aromatics;[11,12] however, anion-π interactions involving electron-rich, negative Θ_{zz} aromatics should be considered experimentally tenable.

Acknowledgment. This work was partially supported by the National Center for Supercomputing Allocations (CHE050026) and utilized the IBM p690 system.

Supporting Information Available: Bond distances, angles, energies (in hartrees), frequency data (thermal energy and number of imaginary frequencies) and quadrupole moment tensor components. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) (a) Meyer, E. A.; Castellano, R. K.; Diederich, F. *Angew. Chem., Int. Ed.* **2003**, *42*, 1210−1250. (b) Ma, J. C.; Dougherty, D. A. *Chem. Rev.* **1997**, *97*, 1303−1324. (c) Dougherty, D. A. *Science* **1996**, *271*, 163−168. (d) Gokel, G. W.; Barbour, L. J.; Ferdani, R.; Hu, J. *Acc. Chem. Res.* **2002**, *35*, 878−886.

(2) Jones, G. B. *Tetrahedron* **2001**, *57*, 7999−8016.

(3) (a) Cashin, A. L.; Petersson, E. J.; Lester, H. A.; Dougherty, D. A. *J. Am. Chem. Soc.* **2005**, *127*, 350−356. (b) Zacharias, N.; Dougherty, D. A. *Trends Pharmacol. Sci.* **2002**, *23*, 281−287.

(4) Weber, M. E.; Elliott, E. K.; Gokel, G. W. *Org. Biomol. Chem.* **2006**, *4*, 83−89.

(5) Gromiha, M. M.; Suwa, M. *Int. J. Biol. Macromol.* **2005**, *35*, 55−62.

(6) Branduardi, D.; Gervasio, F. L.; Cavalli, A.; Recanatini, M.; Parrinello, M. *J. Am. Chem. Soc.* **2005**, *127*, 9147−9155.

(7) Sorme, P.; Arnoux, P.; Kahl-Knutsson, B.; Leffler, H.; Rini, J. M.; Nilsson, U. J. *J. Am. Chem. Soc.* **2005**, *127*, 1737−1743.

(8) Gowrisankar, S.; Lee, K. Y.; Kim, S. C.; Kim, J. N. *Bull. Korean Chem. Soc.* **2005**, *26*, 1443−1446.

(9) (a) Quinonero, D.; Garau, C.; Frontera, A.; Ballester, P.; Costa, A.; Deya, P. M. *J. Phys. Chem. A* **2005**, *109*, 4632−4637. (b) Garau, C.; Frontera, A.; Ballester, P.; Quinonero, D.; Costa, A.; Deya, P. M. *Eur. J. Org. Chem.* **2005**, 179−183. (c) Garau, C.; Frontera, A.; Quinonero, D.; Ballester, P.; Costa, A.; Deya, P. M. *Chem. Phys. Lett.* **2004**, *392*, 85−89. (d) Rosokha, Y. S.; Lindeman, S. V.; Rosokha, S. V.; Kochi, J. K. *Angew. Chem., Int. Ed.* **2004**, *43*, 4650−4652. (e) Kim, D.; Tarakeshwar, P.; Kim, K. S. *J. Phys. Chem. A* **2004**, *108*, 1250−1258. (f) Mascal, M.; Armstrong, A.; Bartberger, M. D. *J. Am. Chem. Soc.* **2002**, *124*, 6274−6276. (g) Quinonero, D.; Garau, C.; Rotger, C.; Frontera, A.; Ballester, P.; Costa, A.; Deya, P. M. *Angew. Chem., Int. Ed.* **2002**, *41*, 3389−3392.

(10) (a) Garau, C.; Quinonero, D.; Frontera, A.; Ballester, P.; Costa, A.; Deya, P. M. *J. Phys. Chem. A* **2005**, *109*, 9341−9345. (b) Zheng, W.; Wong, N.-B.; Tian, A. *J. Phys. Chem. A* **2005**, *109*, 1926−1932.

(11) (a) Gamez, P.; van Albada, G. A.; Mutikainen, I.; Turpeinen, U.; Reedijk, J. *Inorg. Chim. Acta* **2005**, *358*, 1975−1980. (b) Fairchild, R. M.; Holman, K. T. *J. Am. Chem. Soc.* **2005**, *127*, 16364−16365. (c) Demeshko, S.; Dechert, S.; Meyer, F. *J. Am. Chem. Soc.* **2004**, *126*, 4508−1509.

(12) Berryman, O. B.; Hof, F.; Hynes, M. J.; Johnson, D. W. *Chem. Commun.* **2006**, 506−508.

(13) A previous study suggested anion−arene complexes involving negative Θ_{zz} aromatics were observed in solution; however, based on the systems studied and the figures presented in the publication it appears that the binding energy was probably due to arene−arene face-to-face interactions. Schneider, H.-J.; Werner, F.; Blatter, T. *J. Phys. Org. Chem.* **1993**, *6*, 590−594.

(14) Battaglia, M. R.; Buckingham, A. D.; Williams, J. H. *Chem. Phys. Lett.* **1981**, *78*, 421−423.

(15) (a) Tsuzuki, S.; Yoshida, M.; Uchimaru, T.; Mikami, M. *J. Phys. Chem. A* **2001**, *105*, 769−773. (b) Cubero, E.; Luque, F. J.; Orozco, M. *Proc. Natl. Acad. Sci. U.S.A.* **1998**, *95*, 5976−5980.

(16) (a) Garau, C.; Frontera, A.; Quinonero, D.; Ballester, P.; Costa, A.; Deya, P. M. *Chem. Phys. Lett.* **2004**, *399*, 220−225. (b) Garau, C.; Frontera, A.; Quinonero, D.; Ballester, P.; Costa, A.; Deya, P. M. *J. Phys. Chem. A* **2004**, *108*, 9423−9427.

(17) Lewis, M.; Wu, Z.; Glaser, R. Chapter 7 In *Anisotropic Organic Materials − Approaches to Polar Order*; Glaser, R., Kaszynski, P., Eds.; ACS Symposium Series, American Chemical Society: Washington, DC, 2001; Vol. 798, pp 97−111.

(18) Amicangelo, J. C.; Armentrout, P. B. *J. Phys. Chem. A* **2000**, *104*, 11420−11432.

(19) (a) Simon, S.; Duran, M.; Dannenberg, J. J. *J. Chem. Phys.* **1996**, *105*, 11024−11031. (b) Boys, S. F.; Bernardi, F. *Mol. Phys.* **1970**, *19*, 553−566.

(20) Morokuma, K. *J. Chem. Phys.* **1971**, *55*, 1236−1244. (b) Kitaura, K.; Morokuma, K. *Int. J. Quantum Chem.* **1976**, *10*, 325−331.

(21) The MK calculations were performed at the RHF/6-311G level of theory using the MP2(full)/6-311G** optimized geometries. The MK method is only compatible with the RHF method, and we found the 6-311G basis set to work best; when we incorporated polarization or diffuse functions the calculations either did not finish or they gave meaningless results.

(22) *Gaussian 03, Revision C.02*; Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. Gaussian, Inc.: Wallingford, CT, 2004.

(23) Schmidt, M. W.; Baldridge, K. K.; Boatz, J. A.; Elbert, S. T.; Gordon, M. S.; Jensen, J. H.; Kosedi, S.; Matsunaga, N.; Nguyen, K. A.; Su, S. J.; Windus, T. L.; Dupuis, M.; Montgomery, J. A. *J. Comput. Chem.* **1993**, *14*, 1347−1363.

(24) Mecozzi, S.; West, A. P.; Dougherty, D. A. *J. Am. Chem. Soc.* **1996**, *118*, 2307−2308.