Electron Density and Energy Decomposition Analysis in Hydrogen-Bonded Complexes of Azabenzenes with Water, Acetamide, and Thioacetamide

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Ab initio and density functional theoretical studies on hydrogen-bonded complexes of azabenzenes with water, acetamide, and thioacetamide have been carried out to explore the controversy involved in the relative order of their stability in a systematic way. The interaction energies of these complexes have been analyzed using the Morokuma energy decomposition method, and the nature of the various hydrogen bonds formed has been investigated through topological aspects using Bader's atom in a molecule (AIM) theory. Morokuma energy decomposition analysis reveals that the major contributions to the energetics are from the polarization (PL) and charge transfer (CT) energies. From the calculated topological results, excellent linear correlation is shown to exist between the hydrogen-bond length, electron density [$\rho(\mathbf{r})$], and its Laplacian [$\nabla^2\rho(\mathbf{r})$] at the bond critical points for all the complexes considered.

1. Introduction

Hydrogen bonding constitutes one of the most important interactions that play a crucial role in many chemical and biochemical processes.[1,2] The essence of physical interactions that contribute to hydrogen bonding has been the subject of numerous discussions in the literature, and even the nature of interactions involved in an O−H···O hydrogen bond has sometimes been considered to be controversial.[3,4] Studies on the geometry and energy of a number of hydrogen-bonded systems, in particular those involving the new types of hydrogen bonds covering a wide range of interaction energies[5−17] that have come to light in recent years, have considerably enhanced our understanding of this interaction. Among the systems with weak interaction energies, the nonconventional hydrogen bonds such as inverse hydrogen bonding and dihydrogen bonds are responsible for the formation of new types of complexes posing challenging problems in chemistry. Strong hydrogen bonds also have attracted more attention due to their role in several enzymatic mechanisms.[17−21] Thus, such bonds formed within the active sites are responsible for the rate enhancements observed in many enzyme mechanisms, and they affect locally the pK_a values of the systems as well. Among the H-bonds, the N−H···N type bond has received considerably less attention due to its less important role in biological processes, but such bonds found in the hydrogen-bonded complexes of heterocyclic compounds have been studied through their electron density exclusively by Osvald et al.[22]

Azabenzenes are known to be the basic building blocks of oligonucleotides, pharmaceuticals, and polymers and their hydrogen-bonding ability has been studied experimentally as well as theoretically. Thus, Joris et al.[23] have studied the correlation of IR spectral shifts with pK_a values of azabenzene and equilibrium constants of azabenzene−phenol hydrogen-bonded complex. Ab initio methods were employed by Del Bene[24] and Mo[25] for calculating the proton affinity of azabenzenes. Brinck et al.[26] established a relationship between the pK_a values and local ionization energies leading to the relative basicity order for azabenzene as pyridine (PY) > pyridazine (PD) > pyrmidine (PM) > pyrazine (PZ). In an earlier work, Alagona et al.[27] have reported calculations of the azabenzene complexes with water using the 4-31G basis set and showed that the interaction energy order PD > PY > PM does not follow the basicity and proton affinity orders. Similarly Nobeli et al.[28] studied the azabenzene complex with methanol using the intermolecular perturbation theory (IMPT) method and concluded that the hydrogen-bonding ability of azabenzene follows the order PY > PD > PM > PZ. More recently several studies have been carried out to find an explanation for the contradictory results in the order of basicity and proton affinity. Jong et al.[29] have studied experimentally the hydrogen-bonding ability of azabenezene and methyl-substituted azabenezene with thioacetamide, acetamide, and water and concluded that the order of proton affinity is not same as that of the corresponding standard enthalpy. Further, it has also been stated that azabenzene having the anti-form structure has more hydrogen-bond-forming ability as compared to the syn-forms. However, although the nature of hydrogen bonding in these complexes plays a crucial role in determining the basicity and proton affinity of azabenzenes, its detailed investigation has not yet been reported.

The theory of atoms in molecules (AIM) of Bader[30] provides a scheme for partitioning the molecular space into atomic domains through the vanishing gradient of electron density. This theory has proved to be invaluable in the characterization of hydrogen bonding using electron density obtained not only theoretically but also experimentally. Further, Popelier[31−33] has proposed a set of AIM criteria that must be fulfilled for an intermolecular link to be characterized as a true hydrogen bond. In recent years, the topological parameters derived from the AIM theory of Bader have been proved to be a powerful tool for hydrogen-bond analysis. The AIM framework acts as a bridge

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between the quantum chemical methods and experimental methods in quantitative understanding of chemical concepts. The current status of AIM theory is that of a firmly established methodology, and the conceptual picture displayed by the topological aspects of electron density and other related properties is largely independent of the particular approach used to obtain the electron density itself. Recently this approach has been extensively used[34−39] for the studies of interesting and unusal bonding aspects in several molecular systems, including $(H_2O)_2^+$ and $(H_2S)_2^+$.

In this paper, we employ quantum chemical tools to explore the interaction energy of short intermolecular N−H···N bonds and its role in providing stability to the complexes. This quantity is the most important parameter responsible for the observed pK_a values in hydrogen-bonded azabenzene complexes. We have investigated here the N−H···N hydrogen bonds in various azabenzene complexes using the topological aspects of the electron density distribution based on AIM theory. Along with this, we have also studied the interaction energy responsible for the stability of the complexes using Morokuma[40] partitioning of the energy into various components, viz., electrostatic, exchange, polarization, charge transfer, and mix. In this work, we have considered the hydrogen-bonded complexes between various azabenzenes, viz., PY, PD, PM, PZ, with thioacetamide (TA), acetamide (AA), and water (W). We have also studied the effect of methyl substitution on PZ by considering methylpyrazine (MPZ), 2,3-dimethylpyrazine (2,3DMPZ), 2,5-dimethylpyrazine (2,5DMPZ), and trimethylpyrazine (TMPZ) systems.

The outline of the paper is as follows. We discuss the computational method in section 2 and the results of numerical calculations in section 3. Finally, we present the conclusion in section 4.

2. Computational Details

Ab initio and density functional theory (DFT) based methods have been used to investigate the electronic structure of the azabenzene systems considered here. We have taken the geometry for all the considered structures of the complexes from the optimization carried out[29] using DFT with B3LYP exchange-correlation functional[41] and 6-311G(d,p) basis set. Single point calculations were carried out at the B3LYP and MP2 levels using 6-311++G(d,p) basis sets and optimized geometries from B3LYP/6-311G(d,p) calculations. The interaction energies for the complexes were calculated by optimizing the geometry of the monomers using the B3LYP method with the 6-311G(d,p) basis set. The ab initio and DFT calculations in this work have been performed with the GAMESS[42] electronic structure program. The topological properties of the electronic charge density have been calculated with the program AIMPAC.[43]

3. Results and Discussion

The structures of 24 hydrogen-bonded complexes of azabenzene considered here are shown in Figure 1a−c. The calculated interaction energies obtained by subtracting from the energies of the complexes the energies of the corresponding monomers calculated at the same level of ab initio and DFT procedures are reported in Table 1. From the results, it is evident that both B3LYP and MP2 methods predict syn-TA:PD to be the most stable complex, and also the relative order of stability predicted by the two methods is rather similar. Thus, the relative order of stability predicted by MP2 considering syn-forms as well as anti-forms taken together is syn-TA:PD > anti-TA:PD > syn-TA:PY > syn-TA:PM. Similarly DFT with B3LYP predicts the order as syn-TA:PD > syn-TA:PY > syn-TA:PM > anti-TA:PD. There is a small discrepancy in the relative order in the two levels of theories in predicting the second most stable structure, but the difference in energy between them is only 0.03 kcal/mol, which is very small. The present order of stability matches very well with the results of previous studies[29] on the order of stability as predicted from the enthalpies of the thioacetamide−azabenzene complex viz. PD > PY > PM > PZ. A similar order is obtained in our studies for the acetamide and water complexes with azabenzene as well. It is also clear that the hydrogen bond formed with the syn-structure is more stable than that with the anti-form. However, the overall difference in the relative interaction energies for each structure is in the range of 1−2 kcal/mol, which is probably due to the difference in the nature of the hydrogen bond in each structure and needs to be carefully analyzed. The complexation energy values for the thioacetamide through anti-H show a much better correlation with the experimentally determined ΔH values (and also with other experimental quantities; see ref 29 and references therein) than the complexes involving syn-H. This suggests that the formation of the H-bond through the anti-H of thioacetamide is much more favored than through the syn-H, although in the latter case the interaction energies are higher. In view of this, we have confined our analysis only to the anti-conformations for the acetamide−azabenzenes complexes.

The effect of methyl substitution in azabenzene is enhancement of the relative stability of the complexes involving the PZ structure. The increase in interaction energy after methyl substitution in pyrazine complexes is in the range of 0.2−1.5 kcal/mol. Among all the thioacetanide−pyrazine complexes, syn-TA:2,5DMPZ is calculated to be the most stable (with an interaction energy of 9.970 kcal/mol) at the MP2 level of theory, while B3LYP predicts syn-TA:PZ as the most stable one (interaction energy 6.889 kcal/mol). However, among the methyl-substituted complexes, TA:2,5DMPZ is found to be the most stable (interaction energy 6.731 kcal/mol), as predicted by the B3LYP method. Among the anti-forms of methyl-substituted pyrazine complexes, TA:TMPZ is the most stable as predicted by both B3LYP and MP2 method, with an interaction energy of 6.545 and 9.769 kcal/mol, respectively. In all the cases, the syn-form is more stable than the corresponding anti-form at both B3LYP and MP2 levels of theory, except the TA:TMPZ complex, for which the anti-form is more stable as predicted by the B3LYP method.

One of the interesting tools to study the nature of hydrogen-bond energy is provided by Morokuma partitioning of the interaction energy, in which the energy is decomposed in terms of the electrostatic (ES), polarization (PL), exchange-repulsion (EX), and charge transfer (CT) components, including other higher order terms (MIX). The ES term representing the total Coulombic interaction between the free monomer charge distributions includes the interactions of all permanent charges and multipoles and may be either attractive or repulsive. The PL term, which is always attractive, denotes the polarization interaction, i.e., the effect of distortion of the electron distribution of monomer-1 by monomer-2 and vice versa and includes the interactions between all permanent charges or multipoles and induced multipoles. The origin of EX is the interaction caused by the exchange of electrons between the monomers satisfying the Pauli's principle, and this contribution accounts for the short-range repulsion due to overlap of electron distribution of one monomer with that of another. The CT contribution is caused by the electron delocalization interaction, i.e., the interaction caused by charge transfer from the occupied molecular orbital

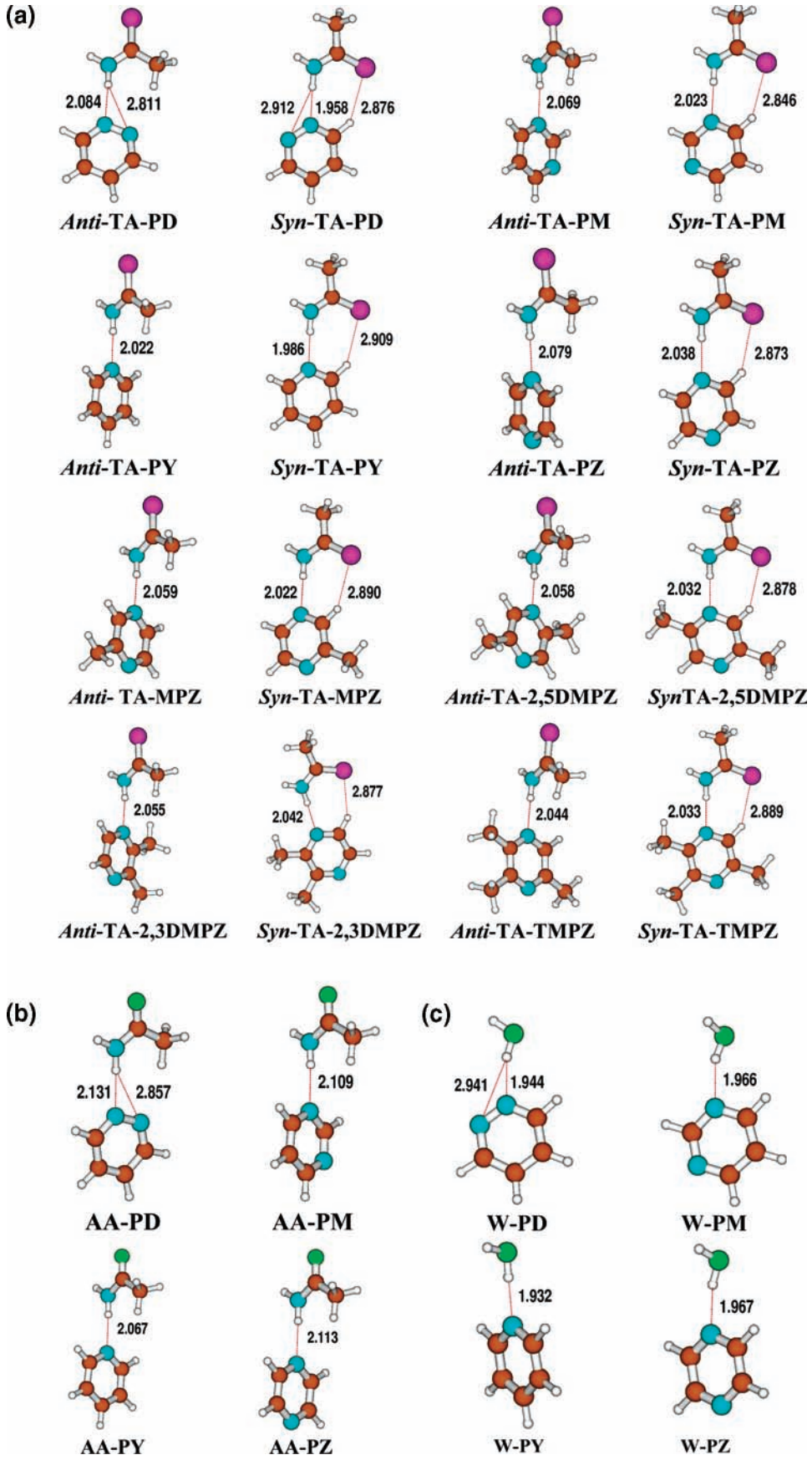

Figure 1. The structures of the (a) thioacetamide−azabenzenes (in both syn- and anti-form), (b) acetamide−azabenzenes and, (c) water−azabenzenes hydrogen-bonded complexes considered in the present work. The hydrogen-bonded complexes between various azabenzenes, viz., pyridine (PY), pyridazine (PD), pyrimidine (PM), pyrazine (PZ), methylpyrazine (MPZ), 2,3-dimethylpyrazine (2,3DMPZ), 2,5-dimethylpyrazine (2,5DMPZ), and trimethylpyrazine (TMPZ) with thioacetamide (TA), acetamide (AA), and water (W) have been considered here.

TABLE 1: Calculated Total Interaction Energies for the Azabenzene Complexes using DFT and MP2 Methods with 6-311++G(d,p) Basis Sets

	ΔE (kcal/mol)						
	B3LYP		MP2			ΔE (kcal/mol)	
system	syn	anti	syn	anti	system	B3LYP	MP2
TA:PY	−7.857	−6.946	−9.945	−9.785	AA:PY	−7.657	−8.644
TA:PD	−9.182	−7.494	−11.795	−9.978	AA:PD	−7.857	−8.794
TA:PM	−7.657	−5.804	−9.626	−8.312	AA:PM	−9.182	−7.379
TA:PZ	−6.889	−5.510	−9.277	−8.218	AA:PZ	−6.889	−7.304
TA:MPZ	−6.442	−5.979	−9.809	−8.705	W:PY	−6.927	−7.799
TA:2,3DMPZ	−6.000	−5.943	−9.433	−9.265	W:PD	−7.656	−8.153
TA:2,5DMPZ	−6.731	−5.967	−9.970	−9.325	W:PM	−6.287	−6.993
TA:TMPZ	−6.111	−6.545	−9.945	−9.769	W:PZ	−6.292	−6.859

TABLE 2: Morokuma Analysis[a] of Interaction Energies[b] (ΔE, kcal/mol) in Thioacetamide−Azabenzene Complexes

	ES		EX		PL		CT		MIX		ΔE		ΔE_{BSSE}[c]	
system	syn	anti	syn	anti	syn	anti	syn	anti	syn	anti	syn	anti	syn	anti
TA:PY	−14.64	−12.52	13.33	9.98	−6.58	−4.13	−3.55	d	5.00	d	−6.44	−6.65	−5.94	−6.13
TA:PD	−16.71	−11.36	14.44	8.07	−7.34	−3.19	−7.88	−2.19	9.48	1.73	−8.00	−6.94	−7.32	−6.30
TA:PM	−14.37	−10.50	12.50	8.38	−6.35	−3.41	−3.45	−2.25	5.07	2.24	−6.59	−5.55	−6.05	−4.99
TA:PZ	−12.97	−9.82	11.71	8.00	−5.56	−3.04	−2.96	−2.07	4.20	1.91	−5.58	−5.02	−5.07	−4.50

[a] For the explanation of different terms see text. [b] Calculated using HF/6-311G(d,p) method. [c] Basis set superposition error corrected interaction energy. [d] Not converged.

TABLE 3: Morokuma Analysis[a] of Interaction Energies[b] (ΔE, kcal/mol) in Acetamide−Azabenzene and Water−Azabenzene Complexes

system	ES	EX	PL	CT	MIX	ΔE	ΔE_{BSSE}[c]
AA:PY	−10.83	8.51	−3.07	−2.22	2.00	−5.60	−5.12
AA:PD	−9.75	6.86	−2.37	−1.80	1.23	−5.82	−5.21
AA:PM	−9.19	7.24	−2.55	−1.26	1.02	−4.74	−4.22
AA:PZ	−8.68	7.03	−2.31	−1.97	1.65	−4.28	−3.79
W:PY	−12.78	11.38	−3.33	−3.12	2.29	−5.57	−4.99
W:PD	−12.40	10.47	−3.09	−2.87	2.10	−5.79	−5.11
W:PM	−11.45	9.84	−2.96	−2.61	2.08	−5.10	−4.57
W:PZ	−10.82	9.73	−2.71	−2.57	1.88	−4.49	−3.95

[a] For the explanation of different terms see text. [b] Calculated using HF/6-311G(d,p) method. [c] Basis set superposition error corrected interaction energy.

of monomer-1 to the vacant molecular orbital of monomer-2 and vice versa. The MIX term is the difference between the total interaction energy and the sum of the above four components and accounts for higher order contributions.

The calculated results from Morokuma analysis using the HF/6-311G(d,p) method are listed in Tables 2 and 3. It is clear from the results that the ES and EX contributions are of the same order of magnitude with opposite sign, thus canceling each other, and that the main contributors that play a significant role in predicting the variation of the overall interaction energies are PL, CT, and MIX. This is further supported by the fact that consideration of the PL, CT, and MIX components alone predicts the syn-TA:PD to be the most stable complex, in agreement with the prediction from the total interaction energy. This structure, in fact, has maximum contribution from all the energy components, viz., PL, CT, MIX. The second most stable structure predicted by this study is anti-TA:PD, in agreement with the MP2 results, although it does not have large contributions from the PL and CT terms. The Morokuma analysis on interaction energies (sum of all the components) rationalizes the order of stability given by syn-TA:PD > anti-TA:PD > anti-TA:PY > syn-TA:PM for thioacetamide−azabenzene complex and PD > PY > PM > PZ for acetamide and water. It is to be noted that even after correction for basis-set-superposition error, the relative interaction energies remain the same. The distribution of the energy components in various structures is shown in Figure 2a−d.

The study of a hydrogen bond through an intuitive picture can be accomplished through the study of electron density based topological parameters, such as the values of the electron density and its Laplacian at the bond critical points (BCPs) of the N−H···N bond. We thus study the nature of interactions involved in the azabenzene hydrogen-bonded complexes within the framework of Bader's topological theory of AIM. A BCP (point corresponding to $\nabla\rho = 0$) is found between each pair of nuclei, which is considered to be linked by a chemical bond with two negative curvatures (λ_1 and λ_2) and one positive curvature (λ_3) denoted as the (3, −1) critical point. The bond ellipticity defined in terms of the two negative curvatures as $\epsilon = (\lambda_1/\lambda_2 - 1)$ reflects the deviation of the charge distribution of a bond path from axial symmetry, thus providing a sensitive measure of the susceptibility of a system to undergo a structural change. The Laplacian of the electronic density ($\nabla^2\rho$) indicates whether the electron density is locally concentrated ($\nabla^2\rho < 0$) or depleted ($\nabla^2\rho > 0$) and provides a detailed map of the basic and acidic regions of a molecule. It is evident that a quantitative comparison of the nature of bonding involved in various azabenzene complexes should follow from the $\nabla^2\rho$ values at BCPs and also from other BCP properties. Thus, $\nabla^2\rho < 0$ at BCPs is unambiguously related to the covalent character of the bond, indicating a sharing of electrons, and is known to be shared interactions, while $\nabla^2\rho > 0$ implies a closed-shell-type interaction found in noble gas repulsive states, ionic bonds, hydrogen bonds, and van der Waals molecules. Apart from this, Bader has also defined a local energy density $E_d(r)$ as $E_d(r) = G(r) + V(r)$ where $G(r)$ and $V(r)$ correspond to kinetic and potential energy densities, respectively. The sign of $E_d(r)$ determines whether accumulation of charge at a given point r is stabilizing ($E_d(r) < 0$) or destabilizing ($E_d(r) > 0$).

The calculated values of the electron density (ρ), Laplacian ($\nabla^2\rho$), bond ellipticity (ϵ), and electronic energy density (E_d) at the BCPs for (N···H) bonds in all the structures with anti- and syn-forms are presented in Tables 4 and 5 (MP2 results). The corresponding B3LYP values are given in Tables S1 and S2 in the Supporting Information. The DFT results on the electron density for the (N···H) bonds in all the structures are similar to the MP2 results. It is expected that the strong bonds are usually associated with higher electron density, indicating higher

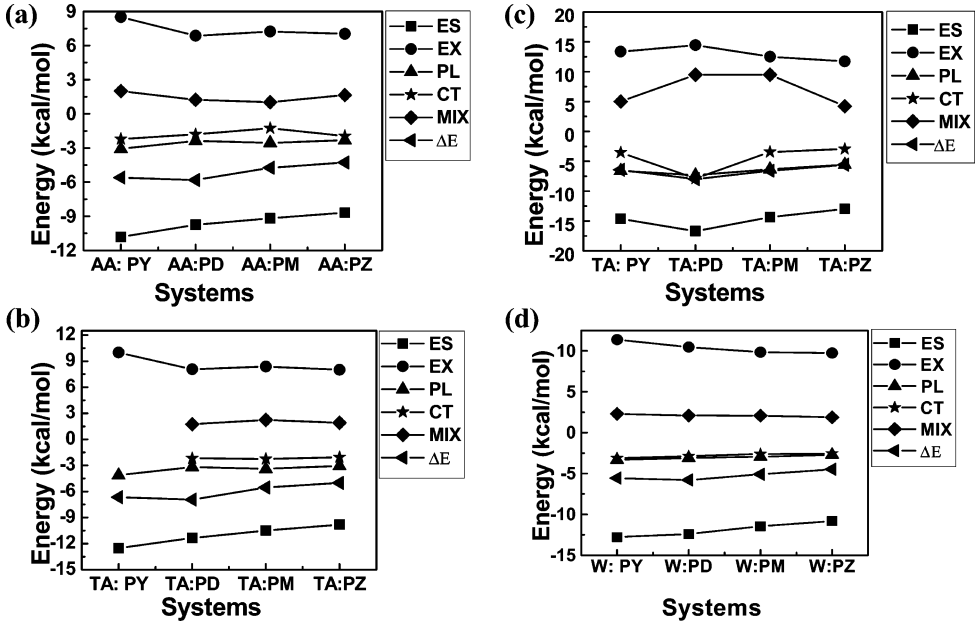

Figure 2. Various energy components as obtained using Morokuma analysis in (a) acetamide−azabenzene complexes, (b) thioacetamide−azabenzene complexes (anti-form), (c) thioacetamide−azabenzene complexes (syn-form), and (d) water−azabenzene complex.

TABLE 4: Topological Analysis of Electron Density (ρ), Laplacian of Electron Density ($\nabla^2\rho$), Ellipicity (ϵ), and Energy Density [E_d(r)] Calculated Using the MP2 Method in Thioacetamide−Azabenzene Complexes (Syn- and Anti-Forms)

	syn						anti					
system	bond	R (Å)	ρ(**r**) (au)	$\nabla^2\rho$(**r**) (au)	ϵ	E_d(r) (au)	bond	R (Å)	ρ(**r**) (au)	$\nabla^2\rho$(**r**) (au)	ϵ	E_d(r) (au)
PY	N···H	1.986	0.0278	0.0683	0.0666	−0.000791	N···H	2.022	0.0262	0.0649	0.0198	−0.000815
	N−H	1.029	0.3220	−1.741	0.0370	−0.487	N−H	1.024	0.3259	−1.753	0.0415	−0.493
PD	N···H	1.968	0.0295	0.0744	0.0767	−0.000724	N···H	2.084	0.0225	0.0576	0.0833	−0.000497
	N−H	1.029	0.3218	−1.740	0.0362	−0.487	N−H	1.021	0.3296	−1.776	0.0421	−0.499
PM	N···H	2.023	0.0254	0.0642	0.0633	−0.000590	N···H	2.068	0.0235	0.0595	0.0154	−0.000608
	N−H	1.026	0.3247	−1.769	0.0378	−0.492	N−H	1.021	0.3289	−1.769	0.0428	−0.498
PZ	N···H	2.038	0.0247	0.0621	0.0652	−0.000626	N···H	2.079	0.0231	0.0580	0.0177	−0.000659
	N−H	1.025	0.3258	−1.764	0.0381	−0.494	N−H	1.021	0.3294	−1.772	0.0429	−0.499
MPZ	N···H	2.021	0.0257	0.0642	0.0646	−0.000680	N···H	2.059	0.0241	0.0601	0.0177	−0.000719
	N−H	1.026	0.3247	−1.768	0.0377	−0.492	N−H	1.022	0.3284	−1.767	0.0425	−0.497
2,3DMPZ	N···H	2.042	0.0247	0.0610	0.0655	−0.000731	N···H	2.055	0.0246	0.0603	0.0171	−0.000816
	N−H	1.026	0.3249	−1.758	0.0381	−0.492	N−H	1.023	0.3277	−1.767	0.0424	−0.496
2,5DMPZ	N···H	2.032	0.0228	0.0624	0.0645	−0.000726	N···H	2.058	0.0244	0.0601	0.0175	−0.000790
	N−H	1.026	0.3246	−1.755	0.0378	−0.491	N−H	1.023	0.3277	−1.762	0.0423	−0.496
TMPZ	N···H	2.033	0.0253	0.0621	0.0651	−0.000770	N···H	2.044	0.0252	0.0617	0.0173	−0.000867
	N−H	1.027	0.3243	−1.754	0.0377	−0.491	N−H	1.023	0.3268	−1.756	0.0421	−0.495

TABLE 5: Topological Analysis of Electron Density (ρ), Laplacian of Electron Density ($\nabla^2\rho$), Ellipicity (ϵ), and Energy Density [E_d(r)] Calculated Using the MP2 Method in Acetamide−Azabenzene and Water−Azabenzene Complexes

	AA						W					
system	bond	R (Å)	ρ(**r**) (au)	$\nabla^2\rho$(**r**) (au)	ϵ	E_d(r) (au)	bond	R (Å)	ρ(**r**) (au)	$\nabla^2\rho$(**r**) (au)	ϵ	E_d(r) (au)
PY	N···H	2.067	0.0237	0.0598	0.0175	−0.000635	N···H	1.932	0.0302	0.0785	0.0175	−0.000503
	N−H	1.020	0.3291	−1.766	0.0454	−0.498	O−H	0.980	0.3413	−1.982	0.0256	−0.578
PD	N···H	2.131	0.0202	0.0530	0.0879	−0.000344	N···H	1.944	0.0292	0.0787	0.0710	−0.000264
	N−H	1.016	0.3322	−1.785	0.0461	−0.503	O−H	0.979	0.3430	−2.001	0.0252	−0.582
PM	N···H	2.108	0.0215	0.0555	0.0130	−0.000457	N···H	1.966	0.0275	0.0750	0.0423	−0.000257
	N−H	1.017	0.3316	−1.778	0.0465	−0.502	O−H	0.978	0.3451	−2.004	0.0256	−0.584
PZ	N···H	2.113	0.0214	0.0549	0.0151	−0.000508	N···H	1.967	0.0277	0.0737	0.0299	−0.000349
	N−H	1.017	0.3318	−1.780	0.0466	−0.502	O−H	0.978	0.3452	−2.005	0.0258	−0.585

structural stability, as is observed for the structure TA:PD, which has higher electron density and higher stability. The trend of stability order predicted by the overall energy minimization and Morokuma interaction energy analysis is augmented by the electron density values calculated at the bond critical points. This observation is also true for the case of azabenzene with acetamide and water. The calculated values of other properties at the BCPs, namely, the Laplacian of the electron density and the bond ellipticity, also follow the same trend. On the other hand, the BCP energy density values using DFT for the (N···H) bonds in all the structures are found to be greater than the corresponding MP2 results. We have also analyzed the electron density distribution around the N−H bond along with the relevant BCP properties. The results reveal that these bonds are highly covalent in nature, as indicated by the large and negative values of the Laplacian obtained through both DFT and MP2 methods, and can be considered to be normal covalent bonds. As far as the relative values of electron density and other properties as obtained by DFT and MP2 methods are concerned, everything is consistent. However, it is also important here to

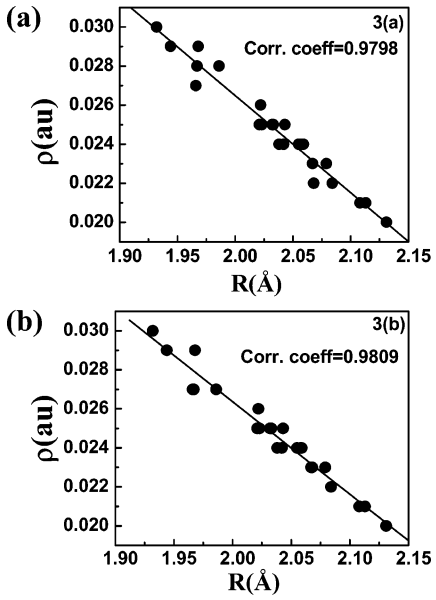

Figure 3. The correlation between electron density at the bond critical point and the hydrogen-bond distance at (a) B3LYP and (b) MP2 levels respectively for all the systems considered in this work.

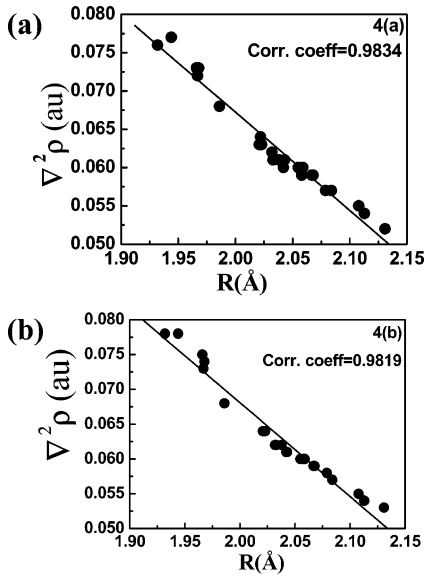

Figure 4. The correlation between the Laplacian of the electron density at the bond critical point and the hydrogen-bond distance at (a) B3LYP and (b) MP2 levels respectively for all the systems considered in this work.

compare the relative values of the electron density and other properties of the individual structures of each complex. The syn-form of the azabenzene−thioacetamide systems has slightly higher values for the electron density and its Laplacian at BCPs as compared to the corresponding anti-form. This trend is in agreement with the higher interaction energies (see Table 1) for the syn-complexes. In this context, it should be noted that in syn-complexes, apart from the N···H hydrogen bond, BCPs exist also for the S···H bonds (see Figure 1a). The electron density at the S···H BCP ranges from 0.007 to 0.008 and the corresponding Laplacian is on the order of 0.02, indicating the presence of a very weak bond. However, this weak interaction for the syn-complexes may aid the overall stability and this may be the reason for the higher interaction energies for the syn-complexes as compared to the anti-complexes. It may also be noted that for the complexes involving PD there is one additional N···H bond, the length of which lies in the range from 2.80 to 2.94 Å. However, the AIM analysis for this kind of bond reveals that no BCPs exist and therefore its contribution toward binding may be negligible.

The overall conclusions on hydrogen bonding can thus be drawn only through a comparison of various electron density based local properties (Bader's analysis) for different systems (here thioacetamide, acetamide, and water). The interaction of azabenzene with water involves large values for the topological parameters, which are followed by thioacetamide and acetamide.

Further, we have been able to establish a correlation between the hydrogen-bond distance, electron density, and its Laplacian. The curves corresponding to the correlation fit are shown in Figures 3a,b and 4a,b. The correlation between the hydrogen-bond length and electron density is inverse, that is, an increase in bond length corresponds to a decrease in the electron density, which is expected, since increase in distance results in reduced orbital overlap and hence low electron density along the bond. The Laplacian of electron density and the hydrogen-bond length also reveal an inverse correlation, analogous to the correlation between electron density and hydrogen-bond length. The correlation coefficient for the electron density and its Laplacian with hydrogen-bond distance for B3LYP and MP2 methods are 0.980, 0.983 and 0.981, 0.982, respectively.

Another property at BCPs studied here is the bond ellipticity. In this work, the values of hydrogen-bond ellipticity in general for all the structures considered here are in the range of 0.01. If we further differentiate between the anti- and syn-forms of TA: azabenzene complexes, the magnitude of the ellipticity values for the syn-form is found to be marginally higher as compared to the anti-form, indicating a possibility of structural change in the syn-form under external perturbations. Among the three systems TA:azabenzene, AA:azabenzene, and W:azabenzene, the bond ellipticity values for the syn-TA complex are found to be relatively higher, indicating that the syn-TA−azabenzene complexes are highly prone to structural changes.

In continuation of the hydrogen-bond analysis at BCPs, we have looked at another parameter, viz., the local energy density. The values of energy density are reported in Tables 4 and 5. As it is well-known that the energy density $E_d(r)$ is an indicator of the charge accumulation, which can distinguish the bonds of stabilizing nature from the destabilizing ones. From the present results, it is clearly evident that the hydrogen bonds formed in all the structures are stabilizing in nature. In the case of methyl substitution, the energy density values are found to increase with the number of methyl groups as one passes from mono- to trimethyl derivatives. This reveals that substitution of azabenzene affects the hydrogen bond.

Although the detailed analysis as discussed above has been very useful in rationalizing the stability of various complexes, it would be interesting to correlate the total interaction energies (reported in Table 1) with some simple electrostatic effects, e.g., the dipole moment of the azabenezenes. It is known that PD (*o*-diazine) has larger and the PM and PZ (*m*- and *p*-diazines respectively) have smaller overall dipole moments as compared to PY (pyridine) because of the addition of the bond dipoles. The trend in the total interaction energy follows this behavior, where the complexes involving PD are associated with higher interaction energy. In view of this, we have plotted the calculated dipole moment against the calculated overall interaction energy values. Very good correlation between dipole moment and the basis set superposition error corrected interaction energy has been observed for the complexes of thioacetamide−azabenzene involving syn-H and is reported in Figure 5. However, for the other complexes, this correlation is not very satisfactory. Thus,

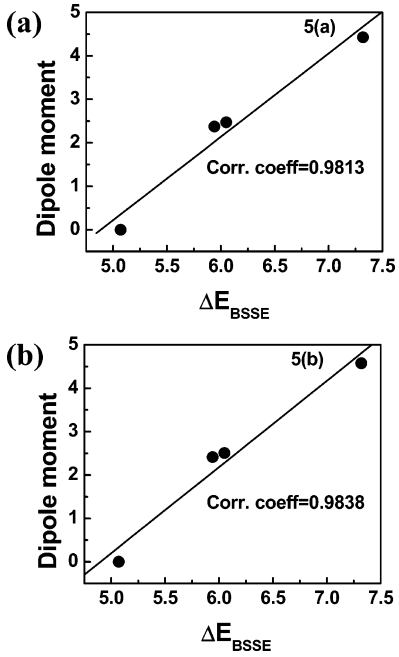

Figure 5. The correlation between the dipole moment and the basis set superposition error corrected interaction energy of thioacetamide−azabenzene complex (syn-form), calculated at (a) B3LYP and (b) MP2 levels.

it is evident that the electrostatic effect is prominent in the syn-form in comparison with the anti-form structure. It is interesting to note that the most stable syn-complexes for which very good correlation exists between dipole moment and interaction energy are also associated with highest stability in terms of the total overall interaction energy as well as BCP electron density parameters.

4. Conclusion

Our results on azabenzene hydrogen-bonded complexes have improved the previous studies. The higher level quantum chemical calculations have provided the most stable structure and relative stability order based on the interaction energy. Among all the thioaccetamide−azabenzenes complexes, the syn-TA:PD has been found to be the most stable one as predicted by both B3LYP and MP2 methods. Similarly, both the methods predict W:PD as the most stable one. However, for the acetamide−azabenzene complexes AA:PM has been found to be most stable at the B3LYP level of theory, although MP2 method predicts AA:PD as the most stable one. These have been well rationalized by Morokuma partitioning of energy, where it has been found that the attractive PL and CT terms are largest for syn-TA:PD complex. Similarly, for the water−azabenezenes complexes, larger PL and CT terms along with a smaller EX term (which is repulsive) are responsible for the largest stability of W:PD complex. The same trend has also been observed for the AA:PD complex. In a similar way, the ES term has been found to be larger for the most stable complex. The overall stability order for the azabenzenes predicted through the present calculations agrees with that based on experimentally measured enthalpy values. These results have been analyzed using the AIM methodology, where the topological properties calculated at bond critical point gives a proper explanation for the stability of a structure. From the calculated topological results, excellent linear correlation has been demonstrated to exists between the hydrogen-bond length, electron density [$\rho(\mathbf{r})$], and its Laplacian [$\nabla^2\rho(\mathbf{r})$] at the bond critical points for all the complexes considered.

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Supporting Information Available: Tables S1 and S2 reporting the calculated values of the electron density (ρ), Laplacian ($\nabla^2\rho$), bond ellipticity (ϵ), and electronic energy density (E_d) at the BCP for N···H bonds in all the complexes of thioacetamide−azabenzenes (both anti- and syn-forms), acetamide−azabenzenes, and water−azabenzenes at the B3LYP level. This material is available free of charge via the Internet at http://pubs.acs.org.

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