Hydrogen Bonding to π-Systems of Indole and 1-Methylindole: Is There Any OH···Phenyl Bond?

Ru Bo Zhang, Ken R. F. Somers, Eugene S. Kryachko,[†] Minh Tho Nguyen, Thérèse Zeegers-Huyskens, and Arnout Ceulemans*

Department of Chemistry, University of Leuven, Celestijnenlaan 200F, B-3001 Leuven, Belgium

Received: May 14, 2005; In Final Form: June 24, 2005

The weak hydrogen-bonded complexes between proton donors and the π-cloud of indole and 1-methylindole (MI) are investigated theoretically by three different methods: DFT/B3LYP, MPW1B95, and MP2. This study addresses the question as to whether the 1:1 complex can only form between the proton and the π-cloud of the pyrrole part of indole or if there also exists a 1:1 complex between the proton and the π-cloud of the phenyl ring. For the water−indole system, the more elaborate MP2 and MPW1B95 methods yield only one minimum with a hydrogen bond to the pyrrole part and weak secondary interactions to the phenyl ring, in agreement with a recent criticism by Van Mourik (*Chem. Phys.* **2004**, *304*, 317−319) that the B3LYP functional is unable to account for the dispersion interaction. However, for the 1:1 complexes between MI and 2-propanol, all three methods indicate that both the five-membered and the six-membered rings of the indole chromophore can form π-complexes. For the MI-trifluoroethanol (TFE) system, it is shown that the ethanol conformation is specific for the interaction site: for the complex to the five-membered ring, TFE is in the cis−gauche conformation, while for the complex to the six-membered ring site, it is in the trans conformation. These results are discussed as a function of local interactions in the systems.

Introduction

A water molecule forms with indole the typical $N-H\cdots OH_2$ complex characterized as a σ-hydrogen bond. In addition, there may exist a π-complex that involves a weak dispersion-rich interaction between the water proton and the π-electron system above the plane of the molecule.[1] Several theoretical works have studied these complexes in detail, mostly using the Kohn−Sham density functional theory (DFT) self-consistent field approach in conjunction with the B3LYP hybrid density functional theory.[2] In a recent investigation of the geometry of the water−indole system within the DFT-B3LYP approach, Somers et al.[3] found, besides of the usual σ-complex, two stable minima of the π-type, one with water above the pyrrole and another, slightly less stable, where the water molecule lies above the phenyl ring of indole. Similar results have also been reported for the complex between water and 1-methylindole that only admit π-complexes since the pyrrole nitrogen site is blocked by the methyl group.[4] These calculations were criticized by Van Mourik[5] who, in an early MP2/aug-cc-pVD(T)Z study with Price and Clary, had found evidence for only one H-bonding structure to the aromatic π-system of the indole, viz., over the pyrrole ring.[6] It was concluded that in contrast to MP2, B3LYP is not adequate to properly describe such π-hydrogen bonding to aromatic rings.

On one hand, this conclusion is certainly valid because the dispersion interactions cannot be fully accounted for by means of semiempirical local exchange-correlation density functionals[7] to which B3LYP does belong. The latter usually underestimates the dispersion forces. Nevertheless, among a plethora of density functionals, there are the PW91 and PBE DFs developed within the generalized gradient approximation, which demonstrate a good performance for complexes with leading dispersion interactions, although less accurate as compared to the correlated wave function based methods.[8] On the other hand, some approaches have recently been developed within the density functional theory that accurately describe the dispersion interactions.[9,8e] It is also worth noticing that the MP2 method is not absolutely perfect in this respect too: it has a well-known tendency to overestimate the correlation energy of neutral systems as the basis set approaches saturation.[10] That is why a usage of moderate basis sets is mostly recommended. This might be a reason of yet another unsatisfactory agreement between experimental and computational results of the water−indole system.[11]

Furthermore, Muñoz et al.[12] have recently studied, both experimentally and computationally, the hydrogen-bonding interactions between 1-methylindole and alcohols using the B3LYP density functional theory. Computationally, they have reported a unique minimum with the hydrogen directed to a C atom of the pyrrole ring of indole (all attempts to locate a minimum with the OH-bond pointing toward the phenyl ring were unsuccessful).[12b]

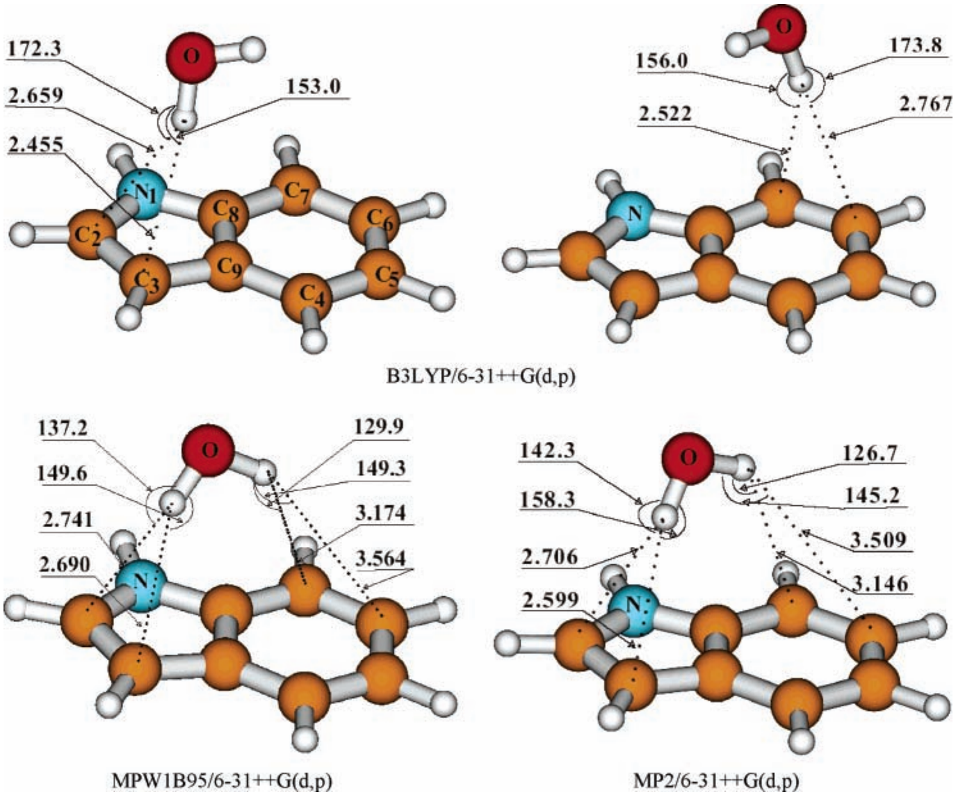
Apparently, there are two issues within the hydrogen bond theory applied to indole systems that demand a more thorough elaboration. One of them is the choice of the preferential computational method and the other is the legitimate problem of whether the OH−phenyl bonding is sufficiently strong or weak. To address these issues, we intend to revisit these π-hydrogen bonded systems, comparing three computational methods and carrying out an extensive search for a subsidiary minimum that involves the phenyl ring.

---

* Corresponding author. E-mail: Arnout.Ceulemans@chem.kuleuven.be; fax: 32-16-327992.

[†] Present address: Department of Chemistry, University of Liège, Sart-Tilman, B-4000 Liège 1, Belgium and Bogoliubov Institute for Theoretical Physics, Kiev, 03143 Ukraine.

10.1021/jp0525437 CCC: $30.25



B3LYP/6-31++G(d,p)

MPW1B95/6-31++G(d,p) MP2/6-31++G(d,p)

Figure 1. Indole-H_2O π-complexes optimized within the B3LYP, MPW1B95, and MP2 approaches.

Computational Methods

The structures reported in the present work were optimized using Becke's hybrid functional B3LYP[13] and the Zhao−Truhlar hybrid meta functional MPW1B95[14] in combination with a 6-31++G(d,p) basis set. The MPW1B95 functional is designed to give improved performance for weak interaction calculations. In addition, we studied these systems with the Møller−Plesset second-order perturbation method (MP2),[15] using the same basis set, and obtained fully optimized structures. Frequency calculations were also performed to account for the zero-point vibrational (ZPE) correction and to analyze the IR data. The basis set superposition errors (BSSE) were computed by the counterpoise (CP) method.[16] All DFT calculations were carried out in Gaussian 03[17] and the MP2 ones in GAMESS.[18]

Results

Three basic systems are studied in the present work: the π-complex of water and indole, the complexes between 1-methylindole (MI, C_9H_8N) and 2-propanol alcohol, and the complexes between 1-methylindole and 2,2,2-trifluoroethanol (TFE, CF_3CH_2OH).

Water−Indole Complex. Figure 1 displays the minimum-energy structures of the water−indole complex by three different computational methods, viz., DFT/B3LYP, DFT/MPW1B95, and MP2. The B3LYP method yields two local minima, as reported earlier for a slightly smaller basis set.[3] As anticipated, a water molecule interacts either with the five-membered ring or with the six-membered ring. Using MP2, we retrieve the results of Van Mourik et al.[6] with a single minimum that partly resembles the pyrrole-oriented complex provided by B3LYP. The MP2 distances of the $OH_w\cdots C_2$ and $OH_w\cdots C_3$ bonds are, respectively, equal to 2.706 and 2.599 Å, which are comparable with the corresponding B3LYP values of 2.659 and 2.455 Å. Upon closer inspection, we notice that the water molecule in the MP2 structure bends over the fused bond of indole and forms, via its second O−H group, weak dispersion contacts with the phenyl carbons C_6 and C_7, characterized by the distances $r(OH_w\cdots C_6) = 3.146$ and $r(OH_w\cdots C_7) = 3.509$ Å. The difference between the B3LYP and the MP2 structures is mainly attributed to the fact that the former underestimates the dispersion forces.

MPW1B95 yields an optimized geometry that almost coincides with the MP2 one, thus confirming the conjecture[14] that this hybrid density functional adequately describes weak van der Waals-type forces. The differences in the bond distances $OH_w\cdots C_2$, $OH_w\cdots C_3$, $OH_w\cdots C_6$, and $OH_w\cdots C_7$ obtained within the MPW1B95 and MP2 methods are, respectively, equal to 0.035, 0.091, 0.055, and 0.028 Å. These results suggest that the less costly MPW1B95 density functional is more practical for these large weakly bound complexes. Interestingly, the (harmonic) frequency analysis conducted within this hybrid meta-density functional reveals the existence of a low-frequency vibrational mode at 47 cm^{-1} that describes a rocking of the water molecule between the pyrrole and the phenyl rings (Figure 2) and thus demonstrates the presence of a very shallow interaction potential that extends over the whole aromatic system.

The calculated interaction energies are summarized in Table 1, including the ZPE and BSSE corrections. The BSSE is more significant in the case of MP2 as compared to the two density functional values. As follows from Table 1, B3LYP underestimates the interaction energy as compared to MP2. It is worth noticing that for the σ-complex of the indole−H_2O system, both methods are mostly consistent: the B3LYP value of 19.82 kJ/mol[3,5] is comparable to the BSSE-corrected MP2 value of 17.15 kJ/mol. Note that the experimental values for the σ-complex of the indole−H_2O system are in the range of 19.52−20.25 kJ/mol.[1c,19] For the studied π-complexes, the MPW1B95 binding energy amounts to 19.57 kJ/mol (Table 1), without the ZPE and BSSE corrections, that is between the B3LYP value of 13.99

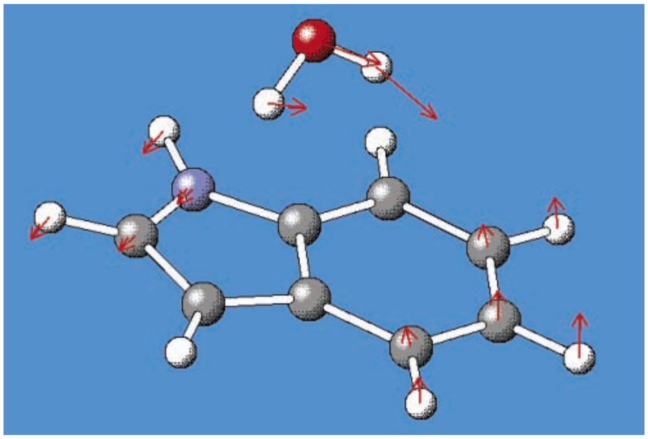


Figure 2. Low-frequency (47 cm^{-1}) rocking vibrational mode in the indole−H_2O (MPW1B95).

TABLE 1: Binding Energies (in kJ/mol) of π-Complexes in the Indole−Water System

	B3LYP			
	five-membered	six-membered	MPW1B95	MP2
E_{int}^{a}	13.99	12.77	19.57	27.07 (26.39)^{b}
E_{int}^{c}	9.20	8.54	13.53	20.83^{d}
E_{int}^{e}	11.09	9.87	15.86	15.55
E_{int}^{f}	6.30	5.56	9.82	9.41^{d}

[a,c,e,f] E_0, E_0 + ZPE, E_0 + BSSE, and E_0 + ZPE + BSSE are used to evaluate E_{int}, respectively. [b] Single-point MP2/6-31++G(d,p) calculations based on MPW1B95/6-31++G(d,p) geometry. [d] ΔZPE from the harmonic frequencies computed via MP2/DZPi.[3]

kJ/mol and the MP2 value of 27.07 kJ/mol. Accounting for the BSSE correction, MPW1B95 gives 15.86 kJ/mol without ZPE and 9.82 kJ/mol after ZPE. These two values accurately reproduce 15.55 and 9.41 kJ/mol obtained correspondingly from the MP2 calculations.

2-Propanol-1-methylindole Complex. The nitrogen atom of MI is unavailable as a proton acceptor; therefore, hydrogen bonding can only occur via the aromatic π-system. It was demonstrated previously that the existence of a single energy minimum structure for the water−indole system is related to its fly over nature that simultaneously exhibits a partial bonding to both rings of indole through the two water O−H bonds. Since the alcohol molecule has a single O−H bond, we postulate the existence of two separate minima on the potential energy surface of interactions between MI and alcohol.

To test the previous hypothesis and also to revisit the puzzling problem of a single minimum raised by Muñoz et al.,[12b] we extend our study to the alcohol−MI complex invoking the previous three computational methods. 2-Propanol is chosen as a representative of the alcohol molecule to model the hexafluoro-2-propanol studied by Muñoz et al.[12] Relative to the adjacent CH group, the OH group of 2-propanol adopts two conformations, the synclinal and antiperiplanar (see Figure 3). The former is slightly favorable by 0.74 kJ/mol ≈ 62 cm^{-1} (B3LYP value). The transition-state linker between these two conformers of 2-propanol is characterized by the transition frequency of 309 cm^{-1} and is placed above the gauche conformer by 444 cm^{-1} (MPW1B95, without ZPE).

Figure 4 shows the optimized geometries of the complexes between MI and 2-propanol in the synclinal conformation, obtained with three different computational methods: B3LYP, MPW1B95, and MP2. Contrary to the indole−H_2O system, all three methods predict two stable hydrogen bonding sites, one at the five-ring and one at the six-ring, thus corroborating the previous hypothesis. In the pyrrole-bonded complex, the OH$\cdots$$C_2$ bond length is equal to 2.558 (B3LYP), 2.824 (MPW1B95), and 2.938 Å (MP2); correspondingly, the OH$\cdots$$C_3$ bond length amounts to 2.564, 2.529, and 2.383 Å. In the phenyl-bonded complex, the OH$\cdots$$C_6$ bond is elongated (3.230, 3.034, and 2.982 Å), while the OH$\cdots$$C_7$ one is shorter (2.550, 2.425, and 2.375 Å). The shortest OH$\cdots$C bonds obey a so-called van der Waals cutoff condition that is necessary to consider them as the conventional π-hydrogen bonds (see, e.g., ref 20 and references therein). The O−H bond of 2-propanol elongates by ≈0.003 Å for both complexes.

The interaction energies evaluated by means of the previous three methods are presented in Table 2. As before, B3LYP provides the lower values as compared to the other methods.

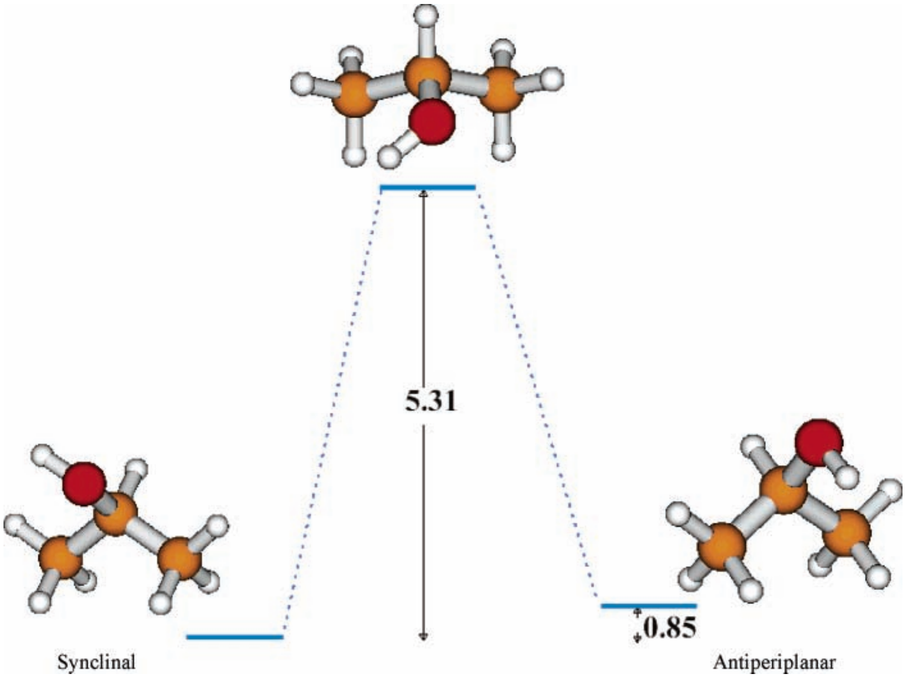


Figure 3. Synclinal and antiperiplanar conformations of 2-propanol and the conformational barrier (MPW1B95).

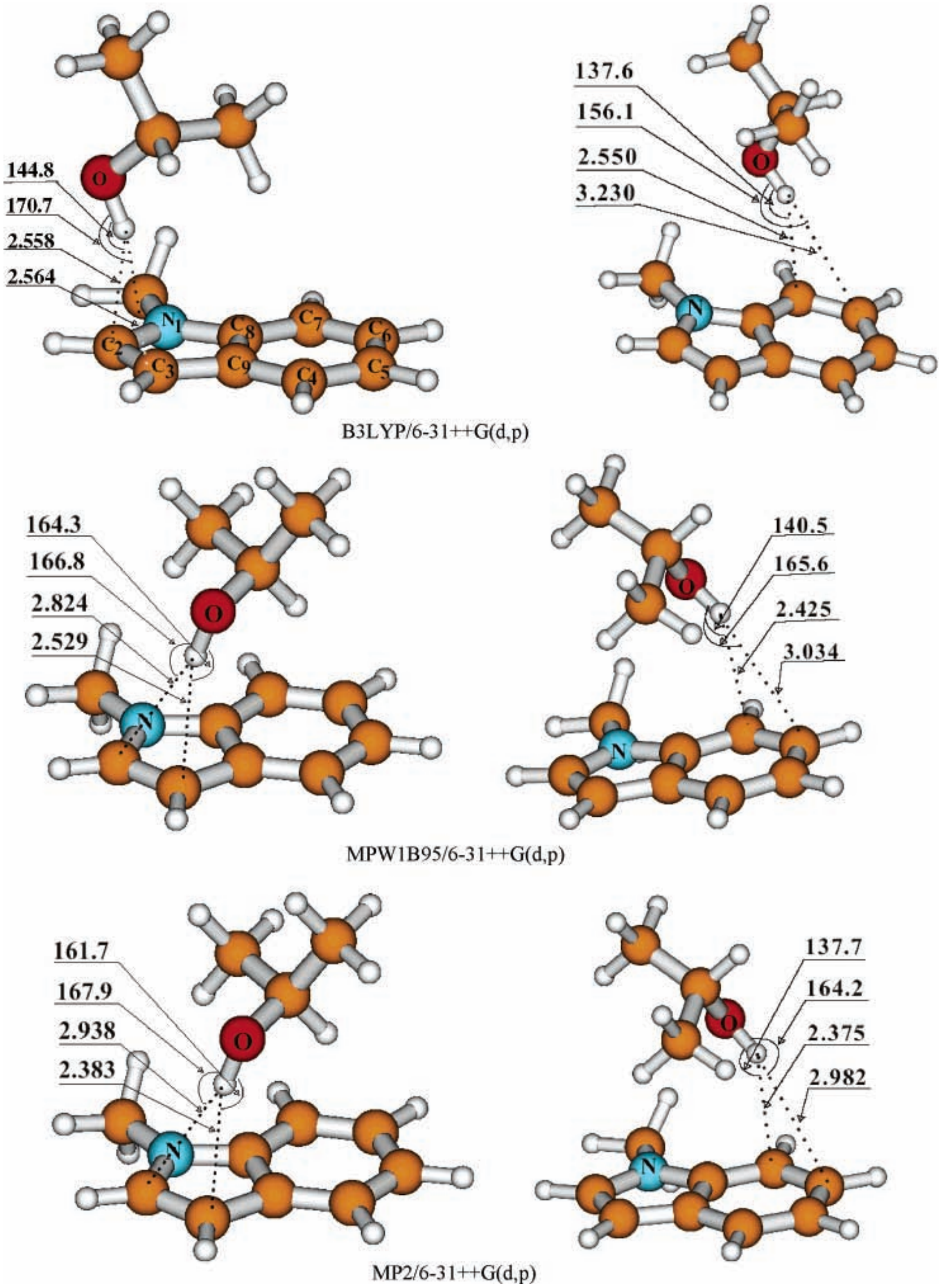


Figure 4. MI-2-propanol π-complexes optimized within the B3LYP, MPW1B95, and MP2 approaches.

TABLE 2: Binding Energies (in kJ/mol) of the 2-Propanol−1-Methylindole π-Complexes

	B3LYP		MPW1B 95		MP2	
	five-membered	six-membered	five-membered	six-membered	five-membered	six-membered
$E_{\mathrm{int}}{}^{a}$	12.78	13.20	18.22	20.82	41.22 (39.49)[b]	43.16 (41.99)[b]
$E_{\mathrm{int}}{}^{c}$	9.55	10.23	13.50	13.22		
$E_{\mathrm{int}}{}^{d}$	10.29	10.83	14.84	17.80	20.93	22.69
$E_{\mathrm{int}}{}^{e}$	7.06	7.86	10.12	10.20		

[a,c,d,e] E_0, E_0 + ZPE, E_0 + BSSE, and E_0 + ZPE + BSSE are used to evaluate E_{int}, respectively. [b] Single-point MP2/6-31++G(d,p) calculations based on MPW1B95/6-31++G(d,p) geometries.

After the BSSE correction and without ZPE, the MP2 interaction energies are twice as large as those of B3LYP. The MPW1B95 method yields interaction energies of 14.84 and 17.80 kJ/mol, to be compared to the MP2 ones, 20.93 and 22.69 kJ/mol. Interestingly, the MP2//MPW1B95 interaction energies using the same basis set agree with the MP2//MP2 ones within 2 kJ/mol.

Since the size of BSSE is found to be strongly dependent on the level of theory, we have also investigated the effect of BSSE on the H-bond distances. For the complex to the six-membered ring, we studied the effect of small translations of the 2-propanol over a range of 0.1 Å along the O···C_7 direction around the respective equilibrium distances for our three different methods. In Table 3, the results of MPW1B95 and MP2 are compared.

TABLE 3: Influence of the BSSE Correction on the O⋯C$_7$ Distance for the 2-Propanol to Six-Membered Ring Complex for MPW1B95 and MP2 Calculations[a]

MPW1B95		MP2	
O⋯C$_7$	E_0 + BSSE	O⋯C$_7$	E_0 + BSSE
3.16	−597.235921	3.08	−595.682964
3.18	−597.236062	3.10	−595.683164
3.20	−597.236131	3.12	−595.683340
3.22	−597.236167	*3.14*	−595.683494
3.24	−597.236153	3.16	−595.683628
3.26	−597.236136	3.18	−595.683741
3.29	−597.236140	3.20	−595.683837

[a] Values in italics correspond to equilibrium distances, based on minimization of the total energy E_0 without the BSSE correction.

TABLE 4: Calculated (Unscaled) Stretching Vibrational Frequencies ν_{OH} (in cm^{-1}) of 2-Propanol, Isolated and Complexed to 1-Methylindole[a]

	B3LYP	MPW1B95
	Isolated 2-propanol	
Synclinal	3822 (16)	3907 (22)
Antiperiplanar	3801 (13)	3885 (17)
	Complex	
five-membered ring	3752 (239)	3858 (137)
six -membered ring	3776 (131)	3853 (104)

[a] The corresponding IR activities (in km/mol) are given in parentheses.

In the case of B3LYP and MPW1B95, variations of BSSE with distance are rather small, 0.2 and 0.5 kJ/mol, respectively. It is gratifying to note that in the case of MPW1B95, the BSSE correction attains a minimum for the equilibrium distance, implying that in this case the BSSE correction does not alter the optimized geometry. On the other hand, for MP2, the BSSE correction amounts to 40% of the binding energy and also varies substantially with distance, 2.15 kJ/mol. In this case, inclusion of BSSE will influence the geometry optimization, as long as the basis set is not yet saturated. These results concur with the findings of Paizs and Suhai.[21]

The MPW1B95 method predicts the low-frequency vibrational modes at 99 and 119 cm^{-1}, corresponding to the π-hydrogen bond stretches with the pyrrole and phenyl rings, respectively. Because of the steric effect that arises between the alcohol and the methyl group at the N atom of MI, the former mode is strongly coupled to the mode that describes the hindered rotation of the methyl group. Table 4 lists the ν_{OH} stretching frequency of the alcohol obtained by the MPW1B95 method, both for the two conformers of the monomer and for the 1:1 complexes. The frequency difference between the two conformers amounts to 22 cm^{-1}.[22] Upon complexation, the ν_{OH} mode of the synclinal conformer exhibits a red shift of 49 and 54 cm^{-1} for the five- and six-membered complexation sites, respectively. Let us notice that owing to the broadness of the IR bands in these complexes, only one absorption will be observed in an experimental spectrum.

Trifluoroethanol-1-methylindole Complex. Having verified the reliability of the MPW1B95 method, we now apply this method to a more detailed study of the complexes between MI and TFE that were investigated by Muñoz et al.[12] using the FTIR technique. The molecule of TFE possesses two minima, corresponding to the trans and cis−gauche conformations[23] displayed in Figure 5. The energy separation between the two is 635 cm^{-1} (MPW1B95, after ZPE). The latter agrees with the value of 681.5 cm^{-1} evaluated at the MP4(SDQ)/cc-pVTZ computational level by Smeyers and co-workers[23] and of 675 cm^{-1} by Mikami and co-workers[24] using MP2/6-31+G(d). The transition state that links the trans and cis−gauche conformers of TFE lies 783 cm^{-1} (MPW1B95, without ZPE) above the latter.

The minimum-energy complexes shown in Figure 6 demonstrate that both the five- and the six-membered rings of MI can form complexes with TFE, although, unexpectedly, the latter exhibits a conformational variance. To the five-membered ring, it favors binding via the cis−gauche conformer. Even if the optimization proceeds from the trans one characterized by the dihedral bond angle χ(HOCC) = 180°, TFE finally adopts the cis form. This contradicts the statement by Muñoz et al.[12b] that only *trans*-TFE is capable of interacting with a large ring system such as indole. Besides, judging from Figure 5 in ref 12b, the B3LYP optimization reported in ref 12b also predicts a *cis*-TFE to a pyrrole form.

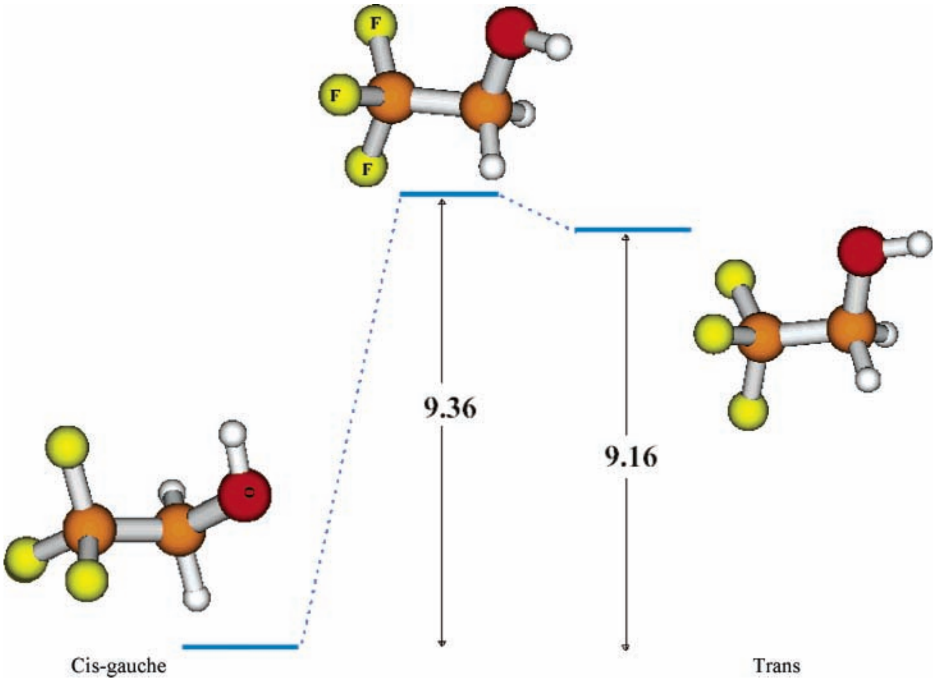


Figure 5. Cis−gauche and trans conformations of TFE and the corresponding transition state (MPW1B95).

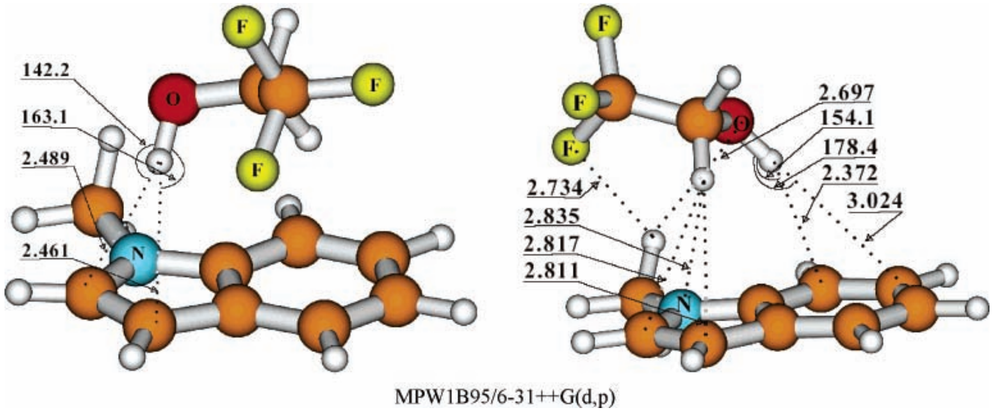


Figure 6. MI-TFE π-complexes optimized with the MPW1B95 method. Complexation to the five-membered ring (left) occurs via the cis conformer, to the six-membered ring (right) via the trans.

TABLE 5: MPW1B95 Binding Energies (in kJ/mol) of the π-Complexes between 1-Methylindole and TFE

	cis conformation five-membered ring	trans conformation six-membered ring
E_0	29.13	23.56
E_0 + ZPE	22.48	16.15
E_0 + BSSE	25.54	19.27
E_0 + ZPE + BSSE	18.89	11.87

TABLE 6: Calculated (Unscaled) OH Vibrational Frequencies ν_{OH} and γ_{OH} of TFE, Isolated and Complexed to 1-Methylindole, Using MPW1B95

	ν_{OH}	γ_{OH}	R_{OH} (Å)[a]
cis TFE	3898 (56)[b]	387 (82)	0.961
trans TFE	3936 (66)	136 (81)	0.959
cis TFE five-membered ring	3810 (166)	665 (123)	0.966
trans TFE six-membered ring	3856 (231)	663 (26)	0.963

[a] The OH distance is given for comparison. [b] IR activity (km/mol).

In further contrast to ref 12b, the present work also finds a complex where the O−H group anchors at the phenyl ring (see Figure 6, right). The global minimum energy structure that TFE adopts in this case is definitely trans. We also found a *cis*-TFE to six-ring complex, but this is much less stable by 8.53 kJ/mol and will not be considered here further.

Selected bond distances are displayed in Figure 6. For the *cis*-TFE to five-ring complex (Figure 6, left), the $OH{\cdots}C_2$ and $OH{\cdots}C_3$ bond lengths are 2.489 and 2.461 Å, respectively. In the *trans*-TFE to six-ring complex, the closest distances are $OH{\cdots}C_7$ and $OH{\cdots}C_6$ at 2.372 and 3.024 Å, respectively. Table 5 lists the interaction energies of the complexes in Figure 6, and corresponding changes in the ν_{OH} and γ_{OH} frequencies of TFE caused by its interaction with MI are reported in Table 6. The length of the O−H bond in TFE is given for comparison. As expected, the stretching frequency correlates well with the bond length elongation. Also note that the frequency of the torsion mode is extremely sensitive to complexation.

Discussion

The B3LYP density functional continues to be widely used for chemical structure and bonding studies including hydrogen bonding. While it accurately enough reproduces the strong water−indole σ-complex, the description of the weaker π-complexes is at variance with the results of more sophisticated methods, as shown in Figure 1 and Table 1. As was previously noted by Van Mourik,[5] the B3LYP density functional stabilizes a water−six-membered-indole complex that is not a true local minimum by the other methods. Upon closer inspection, the reason for this difference becomes clear. In the MP2 optimized structure of water−indole, the two protons of water interact with both rings of the aromatic π-system, although the contact with the phenyl carbons at distances ≥3 Å is extremely weak. At such long distances, B3LYP simply fails. This is also demonstrated when the B3LYP optimization begins from the MP2 minimum: the water molecule returns to its pyrrole-bonded conformer. If, however, the water molecule is replaced by alcohol, containing a single OH group, MP2 demonstrates a coexistence of two stable minima corresponding to the pyrrole and phenyl complexes.

A more thorough study of the MI-TFE system, using the MPW1B95 method, leads to a new and interesting observation that the site of complexation influences the conformation of TFE. Gas phase calculations of the isolated alcohol put the trans conformation above the cis conformation (Figure 5), but it has been shown before that hydrogen bonding can invert this ordering. For example, experimental and theoretical data fully support the existence of a trans form for the NH3-TFE system.[23] The present results show that differences in the complexation site in the same molecule could already trigger this inversion. How to explain this inversion? In the pyrrole complex, all intermolecular contacts other than the $H{\cdots}C2$ and $H{\cdots}C3$ ones are longer that 2.8 Å, indicating that there are no weak interactions between the nonbonded atoms. In contrast, in the phenyl complex, there is a short contact of 2.697 Å between the O atom of TFE and one of the H atoms of the $(N)CH_3$ group, and there is also a short $F{\cdots}H$ contact of 2.734 Å (Figure 6). It must be mentioned that a similar effect has been found in the MI-$(H_2O)_2$ system where a $CH_3{\cdots}O$ interaction seems to attract the lone pair of electrons of the water O.[2a] Further, it should be mentioned that the $O{\cdots}F$ distance equal to 2.763 Å in isolated *trans*-TFE becomes slightly shorter in the *trans*-TFE−phenyl complex (2.753 Å). This indicates that the repulsion between the O and the F lone pairs is not weakened in the complex. In summary, our results show that hydrogen-bond formation favors the most stable cis−gauche geometry not only with small molecules as outlined in ref 23 but also with large molecules such as 1-methylindole.

As shown in Table 6, this conformational change has a pronounced effect on the ν_{OH} shifts: relative to the corresponding conformer, the OH stretching frequencies shift 80 and 88 cm^{-1} in the trans-six-ring and cis-five-ring complex, respectively. The FTIR spectrum in solution shows upon complexation two new bands at 3563 and 3479 cm^{-1}, which are shifted 65 and 149 cm^{-1} with respect to the *cis*-TFE monomer peak. Both absorptions have been assigned to MI-$(TFE)_2$ complexes.[12b] This assignment is, however, questionable, and in view of the experimental conditions, it seems reasonable to assign the band at 3563 cm^{-1} to the 1:1 complexes and the much weaker absorption at 3479 cm^{-1} to the 1:2 complexes.[25,26] It should be mentioned that in the TFE-N-CH_3 pyrrole system, the ν_{OH} band of TFE is red-shifted[26] by 107 cm^{-1}, which is consistent with the larger proton acceptor ability of the π-base. We must also notice that the band at 3479 cm^{-1} is red-shifted by 51 cm^{-1} with respect to the dimer band of TFE observed at 3530 cm^{-1}. This is consisitent with a cooperative strenghtening by the π-hydrogen bond. Notice that a similar red shift with respect to the monomer has been predicted for the $\nu(OH\cdots O)$ vibration of the imidazole−$(H_2O)_2$ complex.[3] As mentioned previously, there is only a small difference between the shifts in the five- and six-ring complexes. This small difference is unlikely to be observed in solution at room temperature where the complex bands are usually broad. More sophisticated techniques such as FTIR spectroscopy in liquefied noble gases will solve this problem.

Conclusion

Throughout the present study, we have confirmed that the B3LYP method unadequately describes very weak π-hydrogen bonding to aromatic π-systems. This explains why this method yields two binding sites for a water molecule above the indole plane, in contrast to more sophisticated methods that predict a unique minimum. We have also shown that for the studied systems, the meta hybrid MPW1B95 density functional provides results close to MP2. This density functional is thus proven to be a rather expedient practical tool that might replace rather expensive MP2 computations. It has further been demonstrated that for the alcohol−MI system, π-complexation is not restricted to the pyrrole site but also can occur on the phenyl ring, with comparable interaction energies. For the TFE alcohol, examined in the recent study by Muñoz et al.,[12] we have found that a change of complexation sites is concomitant with a conformational change. These findings support a new interpretation of the experimental data in terms of two separate 1:1 complexes.

Acknowledgment. Financial support from the Flemish Government through the Concerted Action Scheme is gratefully acknowledged. E.S.K. is the holder of the F.R.F.C. 2.4562.03F (Belgium) fellowship.

References and Notes

(1) (a) Zwier, T. S. *Annu. Rev. Phys. Chem*. **1996**, *47*, 205−241. (b) Carney, J. R.; Hagemeister, F. C.; Zwier, T. S. *J. Chem. Phys.* **1998**, *108*, 3379−3382. (c) Mons, M.; Dimicoli, I.; Tardivel, B.; Piuzzi, F.; Brenner, V.; Millie, P. *J. Phys. Chem. A* **1999**, *103*, 9958−9965.

(2) (a) Carney, J. R.; Zwier, T. S. *J. Phys. Chem. A* **1999**, *103*, 9943−9957. (b) Carles, S.; Desfrancois, C.; Schermann, J. P.; Smith, D. M. A.; Adamowicz, L. *J. Chem. Phys*. **2000**, *112*, 3726−3734. (c) Pejov, L. *Chem. Phys. Lett.* **2001**, *339*, 269−278. (e) Fang, W.-H. *J. Chem. Phys.* **1999**, *111*, 5361−5367.

(3) Somers, K. R. F.; Kryachko, E. S.; Ceulemans, A. *Chem. Phys.* **2004**, *301*, 61−79.

(4) Somers, K. R. F.; Ceulemans, A. *J. Phys. Chem. A* **2004**, *108*, 7577−7583.

(5) van Mourik, T. *Chem. Phys*. **2004**, *304*, 317−319.

(6) van Mourik, T.; Price, S. L.; Clary, D. C. *Chem. Phys. Lett*. **2000**, *331*, 253−261.

(7) (a) Kristian, S.; Pulay, P. *Chem. Phys. Lett.* **1994**, *229*, 175−180. (b) Hobza, P.; Šponer, J.; Reschel, T. *J. Comput. Chem.* **1995**, *16*, 1315−1325. (c) Šponer, J.; Leszczynski, J.; Hobza, P. *J. Comput. Chem.* **1996**, *17*, 841−850. (d) Dobson, J. F. *Int. J. Quantum Chem*. **1998**, *69*, 615−618. (e) Engel, E.; Höck, A.; Dreizler, R. M. *Phys. Rev. A* **2000**, *61*, 32502−32507. (f) Wu, X.; Vargas, M. C.; Nayak, S.; Lotrich, V.; Scoles, G. *J. Chem. Phys.* **2001**, *115*, 8748−8757. (g) Kohn, W.; Meir, Y.; Makarov, D. E. *Phys. Rev. Lett.* **1998**, *80*, 4153−4156.

(8) (a) Wesolowski, T. A.; Parisel, O.; Ellinger, Y.; Weber, J. *J. Phys. Chem. A* **1997**, *101*, 7818−7825. (b) Patton, D. C.; Porezag, D. V.; Pederson, M. R. *Phys. Rev. B* **1997**, *55*, 7454−7459. (c) Zhang, Y.; Pan, W.; Yang, W. *J. Chem. Phys*. **1997**, *107*, 7921−7925. (d) Wesolowski, T. A. *J. Chem. Phys.* **2000**, *113*, 1666−1667. (e) Tran, F.; Weber, J.; Wesolowski, T. A. *Helv. Chim. Acta* **2001**, *84*, 1489−1503. (f) Johnson, E. R.; Wolkow, R. A.; DiLabio, G. A. *Chem. Phys. Lett*. **2004**, *394*, 334−338 and references therein. (g) Meier, R. J. *Chem. Phys. Lett*. **2005**, *401*, 594−594. (h) Johnson, E. R.; Wolkow, R. A.; DiLabio, G. A. *Chem. Phys. Lett*. **2005**, *401*, 595−596.

(9) (a) Pacheco, J. M.; Prates Ramalho, J. P. *Phys. Rev. Lett*. **1997**, *79*, 3873−3876. (b) Hesselmann, A.; Jansen, G. *Chem. Phys. Lett.* **2003**, *367*, 778−784. (c) Misquitta, A. J.; Jeziorski, B.; Szalewicz, K. *Phys. Rev. Lett.* **2003**, *91*, 33201−33205.

(10) (a) Lee, N. K.; Park, S.; Kim, S. K. *J. Chem. Phys*. **2002**, *116*, 7902−7909, 7910−7917. (b) Hobza, P.; Selzle, H. L.; Schlag, E. W. *J. Phys. Chem*. **1996**, *100*, 18790−18794. (c) Šponer, J.; Hobza, P. *Chem. Phys. Lett.* **1997**, *267*, 263−270.

(11) Blanco, S.; Lopez, J. C.; Alonso, J. L.; Ottaviani, P.; Caminati, W. *J. Chem. Phys*. **2003**, *119*, 880−886.

(12) (a) Muñoz, M. A.; Carmona, C.; Balón, M. *Chem. Phys. Lett.* **2004**, *393*, 217−221. (b) Muñoz, M. A.; Galán, M.; Gómez, L.; Carmona, C.; Balón, M. *Chem. Phys. Lett.* **2005**, *401*, 109−114.

(13) (a) Becke, A. D. *J. Chem. Phys*. **1993**, *98*, 5648−5652. (b) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785−789.

(14) (a) Zhao, Y.; Truhlar, D. G. *J. Phys. Chem. A* **2004**, *108*, 6908−6918. (b) Zhao, Y.; Truhlar, D. G. *J. Phys. Chem. A* **2005**, *109*, 4209−4212.

(15) Møller, C.; Plesset, M. S. *Phys. Rev*. **1934**, *46*, 618−622.

(16) Boys, S. F.; Bernardi, F. *Mol. Phys*. **1970**, *19*, 553−566.

(17) 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 03*, Revision C.02; Gaussian, Inc.: Pittsburgh, PA, 2004.

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

(19) Braun, J. E.; Grebner, T. L.; Neusser, H. J. *J. Phys. Chem. A* **1998**, *102*, 3273−3278.

(20) Desiraju, G. R.; Steiner, T. *The Weak Hydrogen Bond*; Oxford University Press: Oxford, 1997.

(21) Paizs, B.; Suhai, S. *J. Comput. Chem*. **1998**, *19*, 575−584.

(22) (a) Asselin, M.; Sandorfy, C. *J. Mol. Struct*. **1971**, *8*, 145−158. (b) Van Der Veken, B. J.; Coppens, P. *J. Mol. Struct.* **1986**, *142*, 359−362.

(23) Senent, M. L.; Niño, A.; Muñoz-Caro, C.; Smeyers, Y. G.; Domínguez-Gómez, R.; Orza, J. M. *J. Phys. Chem. A* **2002**, *106*, 10673−10680.

(24) Venkatesan, V.; Fujii, A.; Ebata, T.; Mikami, N. *J. Phys. Chem. A* **2005**, *109*, 915−921.

(25) The FTIR spectra of the MI-TFE system have been investigated at room temperature in hexane at low concentrations of TFE, MI being in large excess. From the decrease of the intensity of the free ν_{OH} absorption, an association constant of 1.9 M^{-1} was calculated.[12a] It should be mentioned that, using the same experimental conditions, an association constant of 3 M^{-1} was derived for the N−CH_3−pyrrole−TFE complex.[26] A complex band at 3563 cm^{-1} shifted by 65 cm^{-1} from the monomer band was observed for the MI-TFE system. From the same experimental spectra, Muñoz et al.[12b] obtained, after the deconvolution of the FTIR spectra, absorptions at 3567 and 3479 cm^{-1} assigned both to the MI-$(TFE)_2$ complexes. Because the two ν_{OH} vibrations are unlikely to be coupled in the 1:2 complex, the two bands refer probably to the $\nu(H\cdots\pi)$ and to the $\nu(OH\cdots O)$ vibrations. This assignment is rather questionable because, in a large excess of MI, the 1:1 complexes must largely predominate in solution, even if $K_2 > K_1$. Further, the low-frequency band at 3479 cm^{-1} has a much weaker intensity than the band at 3567 cm^{-1}, which is contrary to the expectations. Theoretical calculations of the frequencies are difficult to compare with the present data because, as previously mentioned, the only stable complex found in ref 12b is the *trans*-TFE-pyrrole complex, in complete disagreement with our data.

(26) Muñoz, M. A.; Galán, M.; Gómez, L.; Carmona, C.; Guardado, P.; Balón, M. *Chem. Phys.* **2003**, *290*, 69−77.