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Combined Experimental and Theoretical Study on Hydrogen-Bonded Complexes between Cyclic Ketones, Lactones, and Lactams with 3,4-Dinitrophenol†

M. Esseffar,*,‡ A. El Firdoussi,‡ W. Bouab,‡ J.-L. M. Abboud,§ O. Mó,|| and M. Yáñez||

Département de Chimie Faculté des Sciences Semlalia, Université Cadi Ayyad, Marrakesh, Morocco, Instituto de Quimica Fisica "Rocasolano", CSIC, Serrano, 119, E-28006 Madrid, Spain, and Departamento de Quimica C-9, Universidad Autonoma de Madrid, Cantoblanco, E-28049 Madrid, Spain

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The interaction of 3,4 dinitrophenol (DNP) with cyclic ketones, lactones, and lactams was investigated by UV−visible spectroscopy and density functional theory (DFT) methods. Equilibrium constants K_{HB} for 1:1 hydrogen bonded complexes were determined in solution in CCl_4 and C_6H_{12}. For the entire range of studied bases, the pK_{HB} scale, varying between 2.92 for β-propiolactone to 5.53 for 1-methyl-ϵ-caprolactam, indicates that the basicity increases with the ring size. Geometries, energies, and vibrational characteristics of complexes were obtained by means of DFT calculations. For lactones and lactams, the energy difference between the two most stable conformers, cis and trans, with respect to the ring oxygen (nitrogen) atom, is relatively small, suggesting that the complex observed in solution is probably an equilibrium mixture of both forms. The good correlation between Gibbs free energies in solution and in the gas phase, computed at the B3LYP/6-311++G(3df,2p) level of theory, confirms the reliability of our results. The electron density of the complexes has been analyzed by means of the atoms in molecules (AIM) theory and the natural bond orbital (NBO) method have been used to characterize the orbital interactions. Our theoretical survey shows that the 1:1 complexes are stabilized by a network of conventional and/or nonconventional intermolecular hydrogen bonds.

Introduction

Because of the important role that play hydrogen bonds (HBs) in biological systems, a progressive interest in these interactions, from both experimental and theoretical point of view, has been observed ever since 1960.[1] Several techniques, such as NMR,[2] UV,[3] FTIR,[4] and calorimetry,[5] have been frequently used to characterize them, and a large number of studies, on the HB of neutral species in the gas phase[6] as well as in solution and in the solid state[7−13] were published. Simultaneously, a great deal of efforts were devoted to theoretically characterize these bonds using different computational techniques.[14−19]

In several of the aforementioned studies, the HBs were analyzed in terms of the intrinsic basicity of the HB acceptor toward several alcohols used as reference acids, in particular with respect to phenol derivatives. Taft et al.[20,21] have suggested the use of the pK_{HB} as a measure of HB strength of different HB acceptors toward 4-fluorophenol, which was considered as a good reference acid. Later on, other acids like 3-nitrophenol,[22] 3,5-dichlorophenol,[23] and 3,4-dinitrophenol[24] were used for similar purposes.

Since the early discovery, in 1963, of the existence of C−H−X HBs in some organic structures,[25] the ability of C−H bonds to act as HB donors in determining molecular conformations has been highly recognized. Although in general the C−H−X HBs are weak, they can influence the conformation of biomolecules as well as that of the small molecules. Moreover, C−H donors may participate in the coordination of molecules with the same functionality as OH and NH.[26]

Our interest in HB interactions involving *n*-donor bases and alcohols[27] has lead us to investigate the behavior of a set of cyclic ketones, lactones, and lactams when interacting with 3,4-dinitrophenol, because these interactions should involve a great variety of strong and weak HBs, and because of the biological relevance of these compounds.[28−30]

Hence, we report in this work an experimental and theoretical study of the HB interactions between 3,4-dinitrophenol and a large set of cyclic ketones, lactones, and lactams, namely, cyclopropanone (**1**), cyclobutanone (**2**), cyclopentanone (**3**), cyclohexanone (**4**), cycloheptanone (**5**), oxiran-2-one (**6**), β-propiolactone (**7**), γ-butyrolactone (**8**), δ-valerolactone (**9**), ϵ-caprolactone (**10**), aziridinone (**11**), azetidin-2-one (**12**), pyrrolidin-2-one (**13**), δ-valerolactam (**14**), ϵ-caprolactam (**15**), 1-methylaziridinone (**16**), 1-methylazetidin-2-one (**17**), 1-methylpyrrolidin-2-one (**18**), 1-methyl-δ-valerolactam (**19**), and 1-methyl-ϵ-caprolactam (**20**). To investigate the effects of NO_2 groups on the behavior of these HB complexes, we have investigated also the interaction of 4-fluorophenol and 4-nitrophenol with some selected examples from the three series of compounds included in this study.

Experimental Section

Compounds studied in this work were of commercial Merk origin of the highest purity available. Solvents (CCl_4 and C_6H_{12}) of spectrograde quality were purified according to the literature.[31] A Carry 219 spectrophotometer was used to determine the equilibrium constants for the association between 3,4-dinitrophenol and cyclic ketones, lactones, and lactams in solution by means of UV−visible spectroscopy. Because of the low solubility of 3,4-dinitrophenol in C_6H_{12} and to avoid their self-association, the spectrophotometer measurements were carried out using 10 cm matched silica cells to permit the use of low

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* Corresponding author.
‡ Université Cadi Ayyad.
§ Instituto de Quimica Fisica "Rocasolano".
|| Universidad Autonoma de Madrid.

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TABLE 1: Experimental Values of the Equilibrium Constants K_{HB} and pK_{HB} of Cyclic Ketones-, Lactones-, Lactams-, and 1-Methyl Lactams-3,4-dinitrophenol Complexes

species	$K_{HB}(CCl_4)$	$K_{HB}(C_6H_{12})$	$-pK_{HB}(CCl_4)$	$-pK_{HB}(C_6H_{12})$
2-DNP	$(8.3 \pm 1.1) \times 10^2$	$(18.0 \pm 2.0) \times 10^2$	2.92 ± 0.06	3.26 ± 0.05
3-DNP	$(26.7 \pm 2.7) \times 10^2$	$(30.0 \pm 2.0) \times 10^2$	3.43 ± 0.04	3.48 ± 0.03
4-DNP	$(35.0 \pm 4.0) \times 10^2$	$(40.0 \pm 3.0) \times 10^2$	3.54 ± 0.05	3.60 ± 0.03
5-DNP	$(37.3 \pm 3.7) \times 10^2$	$(39.7 \pm 2.7) \times 10^2$	3.57 ± 0.04	3.60 ± 0.03
7-DNP	$(8.3 \pm 1.2) \times 10^2$		2.92 ± 0.06	3.02 ± 0.26^a
8-DNP	$(31.7 \pm 4.3) \times 10^2$		3.50 ± 0.06	3.62 ± 0.26^a
9-DNP	$(54.7 \pm 5.3) \times 10^2$		3.74 ± 0.04	3.86 ± 0.26^a
10-DNP	$(52.0 \pm 4.0) \times 10^2$		3.72 ± 0.03	3.86 ± 0.28^a
12-DNP	$(3.0 \pm 0.5) \times 10^2$		4.47 ± 0.07	3.55 ± 0.34^a
13-DNP	$(21.7 \pm 3.7) \times 10^2$		5.34 ± 0.07	5.45 ± 0.37^a
14-DNP	$(29.0 \pm 4.0) \times 10^4$	$(34.5 \pm 2.5) \times 10^4$	5.46 ± 0.06	5.54 ± 0.03
15-DNP	$(28.7 \pm 3.7) \times 10^4$	$(34.0 \pm 1.5) \times 10^4$	5.46 ± 0.06	5.53 ± 0.02
18-DNP	$(26.0 \pm 4.0) \times 10^4$	$(33.2 \pm 3.2) \times 10^4$	5.41 ± 0.07	5.52 ± 0.04
20-DNP	$(34.0 \pm 6.0) \times 10^4$	$(36.0 \pm 2.0) \times 10^4$	5.53 ± 0.08	5.56 ± 0.02

[a] The values were deduced from eq 1.

concentrations. In the case of lactams, the initial concentrations were kept under the limit of 3×10^{-3} mol·L^{-1} to prevent self-association of these compounds. The temperature was kept at 298 K. The formation of complexes in CCl_4 and C_6H_{12} was detected easily by the displacement of 3,4-dinitrophenol bands between 340 and 380 nm. The equilibrium constant associated with the formation of complexes between 3,4-dinitrophenol and the bases under consideration is defined as K_{HB}. The procedure used for calculating these equilibrium constants was described by Bellon et al.[32]

Experimental Results

The solvent chosen for this study is C_6H_{12}. For lactones and two lactams (**12** and **13**), the experiment was performed in CCl_4 because of their low solubility in C_6H_{12}. The problem arising from the use of two different solvents in our experiments was solved by unifying the data, following the procedure described previously in the literature,[33] through empirical correlations between pK_{HB} values in these two solvents. K_{HB} and pK_{HB}, measured in CCl_4 and C_6H_{12}, are reported in Table 1. A good linear correlation between the pK_{HB} values in CCl_4 and C_6H_{12} is found:

$$pK_{HB}(C_6H_{12}) = (0.96 \pm 0.03)pK_{HB}(CCl_4) + (0.25 \pm 0.15) \quad (1)$$

with number of data points, $n = 8$; correlation coefficient, $r = 0.99$; and standard deviation, s.d. $= 0.1$.

From the values summarized in Table 1, the following can concluded: (i) The complexes are stabilized through the formation of network of strong hydrogen bonds as suggested by the large K_{HB} and pK_{HB} values. (ii) For a given ring size, except for the small cycles, lactams are more basic than lactones and cyclic ketones. Likely due to the experimental uncertainties, the basicity enhancement, on going from lactams to *N*-methyllactams, is not significant. (iii) Our pK_{HB} values correlate very well with other experimental results in the literature obtained with 4-fluorophenol.[21] The linear correlation fulfils the following equation:

$$pK_{HB(3,4\text{-DNP})} = pK_{HB(4\text{-FP})}(1.7 \pm 0.1) + (1.3 \pm 0.2) \quad (2)$$

with $n = 6$, $r = 0.99$, d.s. $= 0.18$

This correlation shows that the interaction between the investigated compounds and 3,4-dinitrophenol is almost 2 times stronger than that with 4-fluorophenol because (i) there are two attractor NO_2 groups and (ii) as we shall see later, the oxygen atom of the NO_2 group in position 3 is involved in a conventional and an unconventional HB, which enhances the stability of the complexes formed by 3,4-dinotrophenol as a HB donor.

Computational Details

All calculations were performed using density functional methods as implemented in the Gaussian 03 set of programs.[34] Geometry optimizations were carried out using the B3LYP[35−37] hybrid functional with a 6-311+G* basis set.[38] Total final energies were calculated at the B3LYP/6-311++G(3df,2p) level on geometry fully optimized at the B3LYP/6-311+G(d) level. Harmonic vibrational frequencies computed at the B3LYP/6-311+G(d) level.

All molecular structures were confirmed as local minima by the absence of imaginary vibrational frequencies. Zero point vibrational energies (ZPVE) were scaled by the empirical factor 0.98,[39] and the thermal contribution to the enthalpy (TCH) was scaled by the empirical factor 0.9989. Basis set superposition error (BSSE) was calculated using the counterpoise method of Boys and Bernardi.[40] Topological properties of the electronic density were characterized by using the atoms in molecules (AIM) theory.[41−44] The bond critical points (bcp) and the ring critical points (rcp) were located by means of AIMPAC series of programs.[45] Charge distributions were obtained using the natural bond order (NBO) analysis of Weinhold et al.[46]

Computational Results and Discussion

Structures. The carbonyl oxygen is the most basic site for cyclic ketones, lactams, and lactones, as was found in our previous studies.[27,47,48] In the case of lactones and lactams, two orientations of 3,4-dinitrophenol with respect to the base were examined. In the so-called cis conformation, the ring oxygen (nitrogen) atom of the base points in the direction of the 3,4-dinitrophenol molecule, whereas in the so-called trans conformation it points in the opposite direction (see Figures 1a-d).

The total energies calculated at the B3LYP/6-311++G(3df,2p) level, as well as the scaled ZPVE, TCH, and entropy values, evaluated at the B3LYP/6-311+G* level for the complexes and the isolated monomers are reported in Table 1S of the Supporting Information. The majority of the compounds considered

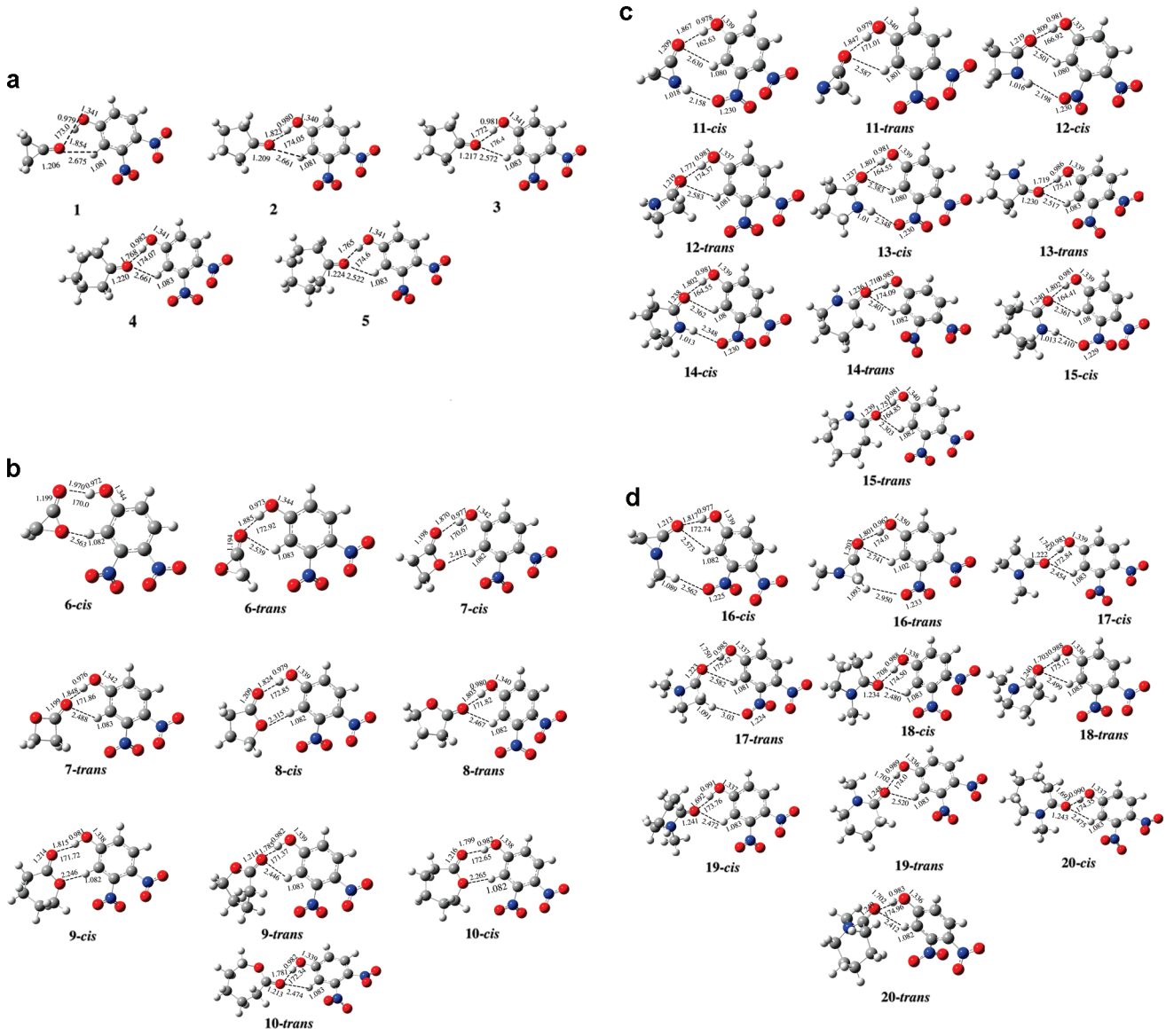

Figure 1. 1-Me lactams. (a) B3LYP/6-311+G* optimized geometries of cyclic ketones-3,4-dinitrophenol complexes. (b) B3LYP/6-311+G* optimized geometries of lactones-3,4-dinitrophenol complexes. (c) B3LYP/6-311+G* optimized geometries of lactams-3,4-dinitrophenol complexes. (d) B3LYP/6-311+G* optimized geometries of 1-methyl lactams-3,4-dinitrophenol complexes.

in this work present several minima on the potential energy surface, which correspond to different conformations. In Figure 1 only the most stable ones have been plotted and some critical bond lengths at B3LYP/6-311+G* level are reported.

The formation of a strong HB between the OH group of the reference acid and the carbonyl group of the base leads a sizable elongation of the C═O bond. This elongation is about 0.009−0.010 Å, in the case of cyclic ketones, 0.011−0.013 Å in the case of lactones, 0.011−0.017 Å in the case of lactams, and 0.011−0.018 Å in the case of *N*-methyllactams. The O−H bond of 3,4-dinitrophenol also lengthens by about 0.013 Å, in the case of cyclic ketones and lactones and about 0.015 Å in the case of lactams and *N*-methyllactams, respectively. These elongations reflect the hydrogen bound strength which is stronger in the latter. Interestingly, when the C−H bond, in the α position to the OH group, is involved in unconventional HB, it shortens by about 0.005−0.009 Å for all studied species. This result is in agreement with similar findings in the literature,[8,27,49,50] where this shortening is attributed to the electron density transfer from the proton acceptor to the proton donor, due to the dominant stabilizing role of the dispersion forces.[49−52] In addition, it is shown that, as the O−H−O angle in hydrogen bonds approaches to 180°, the charge transfer energy increases.[53] The analysis of Figure 1 shows that this angle varies from 173 to about 176° for *N*-methyllactams and cyclic ketones, from 170 to 173° for lactones, and from 163 to 175° for unsubtituted lactams. As we shall see later, this result indicates that the weak charge transfer energy will be in the case of unsubstituted lactams.

Hydrogen Bond Complexation Energies. The interaction energies, ΔE_{el}, calculated as the difference between the energy of the complex (AB) and the sum of the energies of the monomers A (3-4-dinitrophenol) and B (bases),

$$\Delta E_{el} = \mathrm{E(AB)} - [E(\mathrm{A}) + E(\mathrm{B})] \qquad (3)$$

are given in Table 2. These interaction energies include the corresponding ZPVE and BSSE corrections. In the same way $\Delta_r H°$ is the interaction enthalpy calculated as the difference between the enthalpy of the complex (AB) and the sum of the enthalpies of the monomers A and B, and including the thermal corrections evaluated at 298.2 K:

$$\Delta_r H^\circ_m = \Delta_f H^\circ_m(AB) - [\Delta_f H^\circ_m(A) + \Delta_f H^\circ_m(B)] \quad (4)$$

Because the experimental values are obtained in solution with 1 mol/L as standard state and the computational ones are obtained in the gas phase at 298.15 K and 1 atm, which corresponds to a concentration of $c = 4.09 \times 10^{-2}$ mol/L, we have corrected the calculated values by the 1.89 kcal/mol term.[47]

TABLE 2: Calculated Values (in kcal·mol^{-1}) of Selected Thermodynamic State Functions at the B3LYP/6-311++G(3df,2p) Level for Cyclic Ketones-, Lactones-, Lactams-, and *N*-Methyl Lactams-3,4-dinitrophenol Complexes

complex	ΔE_{el}	$\Delta_r H^\circ_m$	$T\Delta_r S^\circ_m$	$\Delta_r G^\circ_m$	$\Delta_r G^\circ_{isom}$	K_{isom}	$\Delta_r G^\circ_{(computed)}$[a]
			Ketones				
1-DNP	−7.44	−6.95	−9.11	0.27			0.27
2-DNP	−8.42	−7.92	−9.14	−0.67			−0.67
3-DNP	−9.61	−9.07	−9.11	−1.85			−1.85
3-4FP	−6.36	−5.81	−8.40	0.70			0.70
3-4NP	−7.94	−7.40	−8.98	−0.31			−0.31
4-DNP	−9.91	−9.37	−9.23	−2.03			−2.03
4-4FP	−6.38	−5.86	−8.56	0.81			0.81
4-4NP	−8.19	−7.64	−8.85	−0.68			−0.68
5-DNP	−10.11	−9.53	−9.13	−2.29			−2.29
			Lactones				
6-DNP-cis	−6.75	−6.09	−7.26	−0.72			
6-DNP-trans	−6.54	−5.89	−6.96	−0.82	−0.10	1.18	−1.18
7-DNP-cis	−7.89	−7.35	−9.02	−0.22			
7-DNP-trans	−7.92	−7.33	−8.27	−0.95	−0.73	3.43	−1.10
8-DNP-cis	−9.80	−9.26	−9.41	−1.74			
8-DNP-trans	−9.55	−9.00	−8.81	−2.08	−0.34	1.77	−2.34
8-4FP-cis	−5.46	−4.86	−8.30	1.55			
8-4FP-trans	−6.37	−5.82	−8.40	0.69	−0.86	4.27	0.56
8-4NP-cis	−7.55	−6.96	−8.84	−0.01			
8-4NP-trans	−7.88	−7.32	−8.79	−0.42	−0.41	2.00	−0.66
9-DNP-cis	−9.82	−9.28	−9.54	−1.63	−0.98	5.23	
9-DNP-trans	−9.77	−9.20	−8.48	−2.61			−2.71
9-4FP-cis	−6.52	−5.95	−8.53	0.69			
9-4FP-trans	−6.80	−6.24	−8.39	0.26	−0.43	2.07	0.03
9-4NP-cis	−7.27	−6.65	−8.59	0.05			
9-4NP-trans	−8.57	−6.96	−8.06	−0.79	−0.84	4.13	−0.92
10-DNP-cis	−11.34	−10.83	−10.17	−2.56			
10-DNP-trans	−10.89	−10.33	−9.08	−3.14	−0.58	2.66	−3.33
			Lactams				
11-DNP-cis	−8.48	−8.14	−10.35	0.32			
11-DNP-trans	−7.95	−7.47	−9.24	−0.12	−0.44	2.10	−0.35
12-DNP-cis	−10.81	−10.57	−10.75	−1.71			
12-DNP-trans	−10.20	−9.82	−9.74	−1.97	−0.26	1.55	−2.26
13-DNP-cis	−11.54	−11.17	−10.55	−2.51			
13-DNP-trans	−11.95	−11.46	−9.10	−4.25	−1.74	18.90	−4.28
13-4FP-cis	−8.47	−8.13	−9.22	−0.80			
13-4FP-trans	−7.96	−7.46	−8.53	−0.82	−0.02	1.03	−1.22
13-4NP-cis	−10.36	−9.94	−8.76	−3.07	−0.81	3.93	−3.20
13-4NP-trans	−9.96	−9.55	−9.18	−2.26			
14-DNP-cis	−12.71	−12.20	−9.18	−4.91	−0.54	2.49	−5.11
14-DNP-trans	−12.58	−12.02	−9.54	−4.37			
14-4FP-cis	−8.69	−8.76	−9.80	−0.85	0.06	1.11	−1.23
14-4FP-trans	−8.25	−7.77	−8.87	−0.79			
14-4NP-cis	−10.21	−10.65	−9.38	−3.16	−0.37	1.87	−3.78
14-4NP-trans	−10.14	−10.64	−9.00	−3.53			
15-DNP-cis	−11.43	−11.01	−10.27	−2.63			
15-DNP-trans	−12.17	−11.68	−9.41	−4.16	−1.53	13.26	−4.20
			N-Methyllactams				
16-DNP-cis	−9.06	−8.47	−9.22	−1.14	−0.07	1.12	−1.52
16-DNP-trans	−8.86	−8.32	−9.14	−1.07			
17-DNP-cis	−11.55	−11.02	−8.58	−4.33	−1.38	10.29	−4.38
17-DNP-trans	−10.97	−10.49	−9.43	−2.95			
18-DNP-cis	−12.63	−12.07	−8.68	−5.28	−1.36	9.95	−5.34
18-DNP-trans	−11.20	−10.60	−8.57	−3.92			
18-4FP-cis	−8.12	−7.15	−8.18	−0.86	−0.14	1.27	−1.20
18-4FP-trans	−8.04	−7.53	−8.70	−0.72			
18-4NP-cis	−9.66	−9.09	−8.93	−2.05			
18-4NP-trans	−10.25	−9.72	−9.03	−2.58	−0.53	2.45	−2.78
19-DNP-cis	−12.96	−12.44	−8.58	−5.75	−0.72	3.37	−5.90
19-DNP-trans	−12.74	−12.22	−9.08	−5.03			
20-DNP-cis	−12.67	−12.13	−8.85	−5.17	−1.34	9.62	−5.23
20-DNP-trans	−12.47	−12.02	−10.08	−3.83			
20-FP-cis	−7.39	−6.82	−8.38	−0.33			
20-FP-trans	−8.14	−7.65	−8.76	−0.78	−0.45	2.14	−1.01
20-NP-cis	−9.67	−9.06	−8.52	−2.43			
20-NP-trans	−10.50	−9.98	−8.88	−2.99	−0.56	2.57	−3.18

[a] Obtained from eq 7 defined in the text.

A perusal of Table 2 shows that lactams are slightly more basic (ca. 1 kcal/mol) than lactones and cyclic ketones. Also, the basicity difference between lactones and their homologue cyclic ketones is relatively small, likely because the inductive effect of the ether like oxygen atom of lactones, which should decrease their intrinsic basicity, is compensated by the unconventional hydrogen bond formed between the oxygen ether and the hydrogen in the α position to the hydroxyl group of 3,4-dinitrophenol.

In terms of ΔE_{el} and $\Delta_r H^\circ$ the majority of cis complexes of lactones are more stable than the trans ones, likely reflecting the stabilizing effect of (a) the unconventional HB between the ether like oxygen of the base and the CH group in α position to the hydroxyl group of 3,4-dinitrophenol and (b) the unconventional HB between CH group in α position to the ether like oxygen of the base and oxygen of the NO_2 group of the reference acid. The situation is similar in lactams where the conventional HB between NH of the base and the oxygen of the NO_2 group of the reference acid contributes to stabilize the cis complexes over the trans ones, although this conventional HB is not very strong because the nitro group is not a very good HB acceptor.

These differences become attenuated in terms of Gibbs free energies, because on the one hand the $T\Delta_r S^\circ_m$ term is, in all cases, rather similar to the $\Delta_r H^\circ_m$ value, leading to rather small complexation free energies. The main contribution to these entropic effects originates in the loss of the translational entropy of the various systems with respect to the separate ones,[54] but at the same time the trans conformers are entropically favored because the reduced number of intermolecular hydrogen bonds results in a less rigid structure for the complex.

It is also worth noting that the unsubstitued lactams are less basic than the methyl substituted ones, because the inductive effects of the methyl group leads to a basicity enhancement of the carbonyl group. However, this effect is partially counterbalanced by the absence of the aforementioned NH···O hydrogen bonds in the methyl derivative.

Because the NO_2 group in position 3 of 3,4-dinitrophenol is usually involved in conventional and unconventional HBs, we considered it of interest to investigate its contribution to the complexation free energy. To accomplish this, we have analyzed the complexation of a subset of bases (five and six member rings of each series) with 4-fluorophenol and 4-nitrophenol as reference acids. In both cases the absence of any substituent at position 3 impedes the formation of HBs with the base, and only the inductive effect of the substituent remains. The corresponding calculated $\Delta_r G^\circ$ values are given in Table 2.

As mentioned above, our calculations show that the relative stabilities of the cis and trans forms, as measured by the corresponding free energy $\Delta_r G^\circ_{DNP}$(calc), are very similar. This means that the HB complexes in the gas phase should be an equilibrium mixture of both isomers and that very likely this is also the situation found in solution, where each form is characterized[48] by the corresponding $K_{HB(DNP)cis}$ and $K_{HB(DNP)trans}$ constants. Unfortunately, the experimental technique used does not allow measuring these constants separately, the actual experimental value, $K_{HB(DNP)}$, given in Table 1 being equal to $K_{HB(DNP)cis} + K_{HB(DNP)trans}$. Hence, to compare the experimental and computational results, it is useful to define the dimensionless equilibrium constant K_{isom} pertaining to the isomerization reaction 5

$$(B\cdots DNP)_{cis} \rightleftharpoons (B\cdots DNP)_{trans} \quad K_{isom,DNP}\Delta_r G^\circ_{isom,DNP} \quad (5)$$

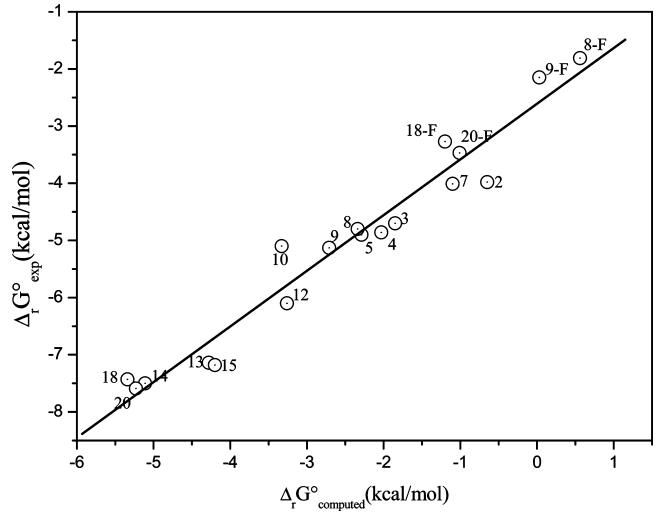

Figure 2. Correlation between $\Delta_r G°_{DNP}$(soln) and $\Delta_r G°_{DNP}$(computed) at B3LYP/6-311++G(3df,2p)//B3LYP/6-311+G(d) for all the studied compounds.

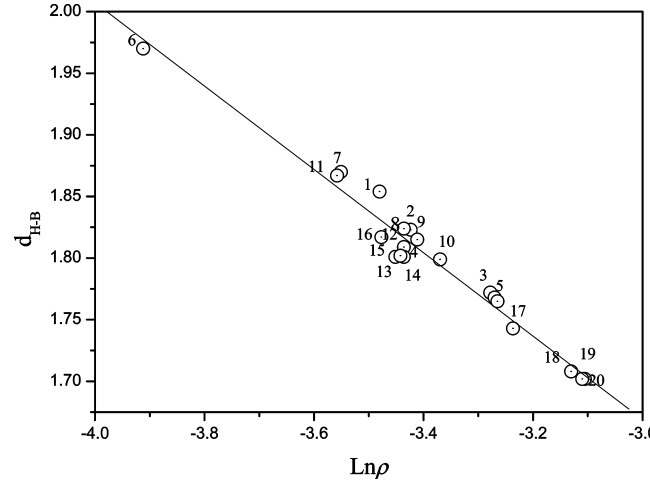

Figure 3. Correlation between the HB distances and the logarithm of the electron density at the OH···O bcp.

Although K_{isom} and $\Delta_r G°_{isom,DNP}$ cannot be experimentally measured, they can be computationally estimated from data in Table 2. The $K_{HB(DNP)}$ for each form, cis and trans, can be easily obtained by calculating his respective free enthalpy $\Delta_r G°_{DNP}$ and $K_{isom,DNP}$:

$$K_{HB(DNP)} = K_{HB(DNP)cis,trans}[1 + K_{isomDNP}] \quad (6)$$

and

$$\Delta_r G°_{DNP} = \Delta_r G°_{(DNP)cis,trans} - RT\ln[1 + K_{isomDNP}] \quad (7)$$

and $\Delta_r G°_{DNP}$ can be easily calculated from data of Table 2. The B3LYP/6-311++G(3df,2p)//B3LYP/6-311+G* calculated values can now be compared with experimental data in solution. As illustrated in Figure 2, there is a quite good linear relationship between both sets of values, which fulfils the equation:

$$\Delta_r G°_{DNP}(exp) = (0.97 \pm 0.05)\Delta_r G°_{DNP}(computed) - (2.61 \pm 0.16) \quad (8)$$

with $n = 18$, $r = 0.977$, and s.d. = 0.34 kcal/mol.

The slope of the plot is close to 1, indicating that the computations satisfactorily reproduce the differential structural effects. The intercept is ca. 2 kcal mol^{-1}, after correction of the standard state. While this might be related to the computational level, it might also reflect that the rather polar HB adducts are stabilized by the solvent (with respect to vacuum).

In this correlation we have introduced also the values obtained for 4-fluorophenol. The slope of the correlation close to unity indicates that the HB interaction of cyclic ketones, lactones, and lactams with regard to 3,4-dinitrophenol is similar in the gas phase and in solution, and therefore cyclic ketones, lactones, and lactams constitute a homogeneous family in terms of structural responses to interaction by hydrogen bonding with 3,4-dinitrophenol.

Characteristics of the HBs. It is to note that both the investigated bases and reference acid behave simultaneously as HB donors and as HB acceptors, showing that the considered compounds are amphiprotic. As indicated above, besides the OH···O conventional HB between the OH group of 3,4-dinitrophenol and the carbonyl oxygen of the base, other unconventional HBs are observed: for example, in the case of lactones the HBs between the hydrogen in the α position to the oxygen ether of the base and the nitro group of the reference acid and the one between the hydrogen in the α position to the hydroxyl group of 3,4-dinitrophenol and the oxygen ether of the lactone. In the case of the trans structure, an unconventional HB was found between the oxygen of carbonyl and the hydrogen in the α position to the hydroxyl group of 3,4-dinitrophenol. In the case of lactams (cis and trans structures), there are also some unconventional HBs between the hydrogen in the α position to the OH group of 3,4-dinitrophenol and the oxygen of carbonyl group. All these HBs are characterized by the existence of a bond critical point (bcp) between the hydrogen of the HB donor and the heteroatom of the HB acceptor.[37] These bcp's exhibit the typical properties of a closed-shell interaction, with a low value of the electron density, ρ_{bcp} and a positive value of its Laplacian. The value of ρ_{bcp} reflects the strength of the bond, and they are larger for conventional HB such as OH···O and NH···O than for unconventional CH···O HBs (Table 2S of the Supporting Information). Similarly, the density at the OH···O bcp increases on going from three- to seven-membered rings, indicating that the strength of the intermolecular HB increases when progressing toward larger cycles. The same remark can be made as far as the NH···O and CH···O bcp's are concerned.

As described previously in the literature[55−58] and as we have found in another work,[27] the HB distances correlate nicely with the logarithm of the electron density at the bcp (Figure 3), the corresponding equation being

$$d_{HB} = (-0.34 \pm 0.02)\ln \rho_{rcp} + (0.65 \pm 0.05) \quad (9)$$

with $n = 20$, $r = 0.97$, and s.d. = 0.01

The topological analysis of the charge density of the considered complexes reveals also the existence of ring critical point (rcp), nicely indicating the existence of the unconventional HBs. Some previous studies[17,59,60] indicated that the charge density at the rcp can be a measure of the strength of the HB in cyclic systems. The values of the electron density at the rcp reported in Table 3S (Supporting Information) clearly show the stability enhancement of the complex with the ring size. This is consistent with the results of the NBO analysis (see Table 3).

TABLE 3: Charge Transfer (e) and Orbital Interaction Energy (kcal/mol) of the Most Stable Complexes

		ΔE_{CT}				
complex	charge transfer	$n_{1O} \rightarrow \sigma^*_{O-H}$	$n_{2O} \rightarrow \sigma^*_{O-H}$	$n_O \rightarrow \sigma^*_{C-H}$	$n_{O(NO2)} \rightarrow \sigma^*_{N-H}$	sum
1	−0.0298	13.03	5.26	0.07		18.36
2	−0.0309	12.88	6.99	0.09		19.96
3	−0.0407	18.76	7.15	0.39		26.30
4	−0.0396	18.02	7.58	0.45		26.05
5	−0.0415	19.32	7.35	0.48		27.15
6	−0.0209	5.16	4.20	0.55		9.91
7	−0.0328	10.51	5.78	1.46		17.75
8	−0.0398	12.75	7.16	2.12		22.03
9	−0.0424	13.33	7.38	2.65		23.36
10	−0.0421	14.56	7.78	2.44		24.78
11	−0.0183	5.62	4.75	0.13	4.16	14.66
12	−0.0230	8.66	3.74	0.46	4.45	17.31
13	−0.0245	9.54	1.30	1.06	3.24	15.14
14	−0.0270	9.60	0.48	1.27	2.50	13.85
15	−0.0271	9.73	0.31	1.29	1.94	13.24
16	−0.0241	8.05	2.57	0.52		11.14
17	−0.0413	9.99	9.09	0.82		19.90
18	−0.0486	14.82	8.62	0.65		24.09
19	−0.0523	17.51	8.19	0.37		26.07
20	−0.0511	17.04	8.47	0.28		25.79

NBO analysis was performed to evaluate different electronic properties of the studied systems. The NBO charges clearly indicate that a considerable charge transfer between the interacting molecules takes place. Also importantly, the larger is the charge transfer the stronger is the interaction. Thus, for a given ring size, the largest transfer is observed in the case of *N*-methyllactams followed by lactones, ketones, and lactams, respectively. It is to note that, as lactams are also proton donors, a certain amount of electronic charge is transferred from the acid, via the oxygen atom of NO_2, to lactams via the hydrogen of NH. Table 3 reports also the stabilization energy values of the orbital interaction within the NBO analysis. It shows that the two lone pairs of the carbonyl oxygen atom contribute to the H-bond. Their contributions are, however, not equal because of their different orientations with respect to σ^*_{O-H}. Another interaction occurs from the lone pair of the oxygen carbonyl to the antibonding orbital of the C−H bond in α position of O−H group. In the case of lactams there is another interaction between the lone pair of the oxygen of NO_2 group and the σ^*_{N-H}. Finally, the NBO analysis shows that the hydrogen bond interactions can take place through these different positions. In terms of charge transfer energy, the combination of the charge transfer through these different ways gives methyllactams more stabilized than, lactones, cyclic ketones, and lactams, in good agreement with the electron density at the bcp and the variation of the O−H−O angles.

Conclusion

Cyclic ketones, lactones, lactams, and methyl lactams with 3,4-dinitrophenol form 1:1 molecular complexes, in tetrachloromethane solution at 25 °C, linked by O−H···O, H−O···HC, and NH···O(NO_2) hydrogen bonds. In this study we have confronted experimental and theoretical data to characterize and identify the formed complexes and to show the amphiprotic character of the bases under investigation as well as the role of conventional and nonconventional hydrogen bonds on the stability of these complexes, whose nature was ratified by both AIM and NBO analyses. In all cases, the conventional ones involve the lone pairs of carbonyl oxygen atom of the base and the σ^*_{H-O} antibonding orbital of the reference acid. In the case of lactams conventional HBs occur between the lone pairs of the NO_2 oxygen atom and the σ^*_{H-N} antibonding orbital. The second nonconventional ones take place between the lone pairs of carbonyl oxygen atom and the σ^*_{H-C} antibonding orbital of the CH group in α position of the OH group. The agreement between experimental free energies in solution, and calculated values in gas phase, is excellent. In the case of lactones, lactams, and methyl lactams, the complexes with 3,4-dinitrophenol are an equilibrium mixture of cis and trans conformers in comparable amounts.

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Supporting Information Available: Tables of energies, entropies, and enthalpies; hydrogen bond lengths, electron densities, and ring critical points. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Pauling, L. , *The Nature of the Chemical Bond*, Ithaca, N. Y., 1960.
(2) Gurka, D.; Taft, R. W. *J. Am. Chem. Soc.* **1969**, *91*, 4794–4801.
(3) Arnett, E. M.; Joris, L.; Mitchell, E.; Murty, T. S. S. R.; Gorrie, T. M.; Schleyer, P. V. R. *J. Am. Chem. Soc.* **1970**, *92*, 2365–2377.
(4) Joesten, M. D.; Drago, R. S. *J. Am. Chem. Soc.* **1962**, *84*, 2037–2039.
(5) Gurka, D.; Taft, R. W.; Joris, L.; Schleyer, P. V. R. *J. Am. Chem. Soc.* **1967**, *89*, 5957–5958.
(6) Marco, J.; Orza, M. J.; Notario, R.; Abboud, J.-L. M. *J. Am. Chem. Soc.* **1994**, *116*, 8841–8842.
(7) Scheiner, S.; Maksic, Z. B. i. , Orville-Thomas., W. J. , Pauling's Legacy-Modern Modelling of the Chemical BondAmsterdam, 1977;Vol. 6.
(8) Jeffrey, G. A. *An Introduction to hydrogen bonding*; Oxford University Press: New York, 1997.
(9) Scheiner, S. *Hydrogen Bonding. A Theoretical Perspective*; Oxford University Press: New York, 1997.
(10) Cox, C.; Lectka, T. *J. Am. Chem. Soc.* **1998**, *120*, 10660–10668.
(11) Filarowski, A.; Glowiak, T.; Koll, A. *J. Mol. Struct.* **1999**, *484*, 75–89.
(12) Barber, S. E.; Dean, K. E. S.; Kirby, A. J. *Can. J. Chem.* **1999**, *77*, 792–801.
(13) Ivancich, A.; Mattioli, T. A. *Photosynth. Res.* **1998**, *55*, 207–215.
(14) Alkorta, I.; Maluendes, S. *J. Phys. Chem.* **1995**, *99*, 6457–6460.
(15) Gonzalez, L.; Mó, O.; Yàñez, M. *J. Phys. Chem. A.* **1997**, *101*, 9710–9719.
(16) Gonzalez, L.; Mó, O.; Yàñez, M.; Elguero, J. *J. Chem. Phys.* **1998**, *109*, 2685–2693.
(17) Gonzalez, L.; Mó, O.; Yàñez, M. *J. Chem. Phys.* **1999**, *111*, 3866.
(18) Rappé, A. K.; Bernstein, E. R. *J. Phys. Chem. A* **2000**, *104*, 6117–6128.
(19) Müller-Dethlefs, K.; Hobza, P. *Chem. Rev.* **2000**, *100*, 143–167.
(20) Taft, R. W. , *Steric Effects in Organic Chemistry,*; Wiley.ed.: New York, 1956;Chap. 13.
(21) Taft, R. W.; Gurka, D.; Joris, L.; Schleyer, P. V. R.; Rakshys, J. W. *J. Am. Chem. Soc.* **1969**, *91*, 4801–4808.
(22) Khan, M.; Imura, H. *Anal. Sci.* **2000**, *16*, 115.
(23) Abboud, J. L.-M.; Sraidi, K.; Guiheneuf, G.; Negro, A.; Kamlet, M. J.; Taft, R. W. *J. Org. Chem.* **1985**, *50*, 2870–2873.
(24) Laurence, C.; Berthelot, M.; Helbert, M.; Sraidi, K. *J. Phys. Chem.* **1989**, *93*, 3799–3802.
(25) Sutor, D. J. *J.Chem. Soc.* **1963**, 1105–1110.
(26) Steiner, T.; Saenger, W. *J. Am. Chem. Soc.* **1993**, *115*, 4540–4547.
(27) El Firdoussi, A.; Esseffar, M.; Bouab, W.; Abboud, J.-L. M.; Mó, O.; Yáñez, M.; Ruasse, M. F. *J. Phys. Chem. A* **2005**, *109*, 9141–9148.
(28) Dean, F. M. *Naturally Occuring Oxygen Ring Compounds*; Butterworths: London, 1963.
(29) Izaki, K.; Matsuhashi, M.; Strommger, J. L. *J. Biol. Chem.* **1968**, *243*, 3180–3192.
(30) Wilhelm, M. P.; Esters, L. *Mayo Clin. Proc* **1999**, *74*, 928–935.

(31) Riddick, J. A.; Bunger, W. B. *Organic Solvents: techniques of Chemestry, 3th ed.*; John Wiley: London, 1970; Vol. 2.
(32) Bellon, L.; Taft, R. W.; Abboud, J.-L. M. *J. Org. Chem.* **1980**, *45*, 1166–1168.
(33) Lamsabhi, A.; Bouab, W.; Esseffar, M.; Alcami, M.; Yáñez, M.; Abboud, J.-L. M. *New J. Chem.* **2001**, *25*, 509–517.
(34) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. J. A.; Stratmann, R. E., Burant, J. C. , Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K., Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A.; *Pittsburgh PA: Gaussian, Inc.Gaussian 98. Revised A3 ed.*; 1998.
(35) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785–789.
(36) Becke, A. D. *J. Chem. Phys.* **1992**, *96*, 2155–2160.
(37) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648–5652.
(38) Frisch, M.; Pople, J. A.; Binkley, J. S. *J. Chem. Phys.* **1984**, *80*, 3265–3270.
(39) Pople, J. A.; Scott, A. P.; Wong, M. W.; Radom, L. *Isr. J. Chem.* **1993**, *33*, 345–350.
(40) Boys, S. F.; Bernardi, F. *Mol. Phys.* **1970**, *19*, 553–566.
(41) Bader, R. F. W.; Bielger-Koning, F. W.; Tang, T. H. *J. Comput. Chem.* **1982**, *3*, 317–328.
(42) Bader, R. F. W.; MacDougall, D. J.; Lau, C. D. H. *J. Am. Chem. Soc.* **1984**, *106*, 1594–1605.
(43) Bader, R. F. W.; Essen, H. *J. Chem. Phys.* **1984**, *80*, 1943–1960.
(44) Bader, R. F. W. *Atoms in Molecules: A Quantum Theory*; Oxford University Press: New York, 1990.
(45) Bader, R. F. W.; Cheeseman, J., The AIMPAC Programs Package.
(46) Reed, A. E.; Curtiss, L. A.; Weinhold, F. *Chem. Rev.* **1988**, *88*, 889–926.
(47) El Firdoussi, A.; Esseffar, M.; Bouab, W.; Lamsabhi, A.; Abboud, J. L.-M.; Mó, O.; Yáñez, M. *New J. Chem.* **2003**, *27*, 1741–1747.
(48) El Firdoussi, A.; Esseffar, M.; Bouab, W.; Abboud, J. L.-M.; Mó, O.; Yáñez, M. *J. Phys. Chem. A* **2004**, *108*, 10568–10577.
(49) Cubero, E.; Ozozeo, M.; Hobza, P.; Luque, P. *J. Phys. Chem. A* **1999**, *103*, 6394–6401.
(50) Lee, K. M.; Chang, H. C.; Jiang, J.-C.; Chen, J. C. C.; Kao, H.-E.; Lin, S. H.; Lin, I. J. B. *J. Am. Chem. Soc.* **2000**, *122*, 11450–11458.
(51) Hobza, P.; Havlas, Z. *Chem. Rev.* **2000**, *100*, 4253–4264.
(52) Tsuzuki, S.; Honda, K.; Uchimaru, T.; Mikami, M.; Tanabe, K. *J. Am. Chem. Soc.* **2002**, *124*, 104–112.
(53) Pakiari, A. H.; Eskandari, K. *J. Mol. Struct. (Theochem)* **2006**, *759*, 51–60.
(54) Esseffar, M.; Herrero, R.; Quintanilla, E.; Davalos, J. Z.; Jimzenez, P.; Abboud, J.-L. M.; Yáñez, M.; Mo, O. *Chem.—Eur. J.* **2007**, *13*, 1796–1803.
(55) Alkorta, I.; Rozas, I.; Elguero, J. *J. Ber. Bunsen-Ges. Phys. Chem.* **1998**, *102*, 429–435.
(56) Alkorta, I.; Rozas, I.; Elguero, J. *Theor. Chem. Acc.* **1998**, *99*, 116–123.
(57) ALkorta, I.; Rozas, I. *Struct. Chem.* **1998**, *9*, 243–247.
(58) Tang, T.-H.; Deretey, E.; Knak Jenson, S. J.; Csizmadia, I. G. *Eur. Phys. J.* **2006**, *D37*, 217–222.
(59) Grabowski, S. J. *J. Phys. Chem. A* **2001**, *105*, 10739–10746.
(60) Sanz, P.; Mó, O.; Yàñez, M. *Phys. Chem. Chem. Phys.* **2001**, *5*, 2942–2947.

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