Nitro derivatives of pyrrole, furan and 1*H*-tetrazole: ring or nitro bases?

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The gas-phase basicity of pyrrole, furan, 1*H*-tetrazole and their nitro derivatives has been analyzed by means of high level *ab initio* and DFT calculations. The gas-phase basicity of 2-nitrofuran was also determined by means of FT-ICR mass spectrometry. Our results indicate that although pyrrole and furan behave as carbon bases in the gas phase, their nitro derivatives protonate preferentially on the nitro group. Conversely, both 1*H*-tetrazole and its 5-nitro derivative protonate preferentially on the ring, because the intrinsic basicity of the nitro group is significantly dampened when the group is attached to a tetrazolic ring. For the 5-nitro-1*H*-tetrazole the most stable protonated species corresponds to an open structure formed by protonation on N1, which is followed by a N1–N2 bond cleavage. This non-cyclic structure is entropically favored and therefore it should be the one observed in ICR measurements.

The gas-phase reactivity of nitroazoles poses some intriguing questions mainly related with the nature of the basic site. A paradigmatic example of such a situation is provided by 3- and 4-nitropyrazole. In the literature it was suggested[1] that the acid-base properties of 3-nitropyrazole could be "abnormal" as compared with those of 4-nitropyrazole. A more recent study[2] carried out by using collisional activation (CA) and neutralization-reionization (NR) mass spectrometry techniques on the protonated species of both nitro compounds revealed that they protonate preferentially on the nitro groups, although there is possibly a small proportion of protonation on the nitrogen atom of the azolic ring. This evidence was in clear contrast with the results obtained by means of high-level *ab initio* calculations carried out at the CCSD(T)/6-31+G* level, which indicated[2] that protonation on the azolic ring nitrogen was clearly favored over protonation on the nitro group. Furthermore, these theoretical estimates were in quite good agreement with the gas-phase proton affinities measured by means of Fourier transform ion cyclotron resonance (FT-ICR) spectrometry.[2] The main conclusion of this study was that very likely 3- and 4-nitropyrazole protonate at the heterocyclic nitrogen, rather than on the oxygen of the nitro group, although, due to the small energy difference between these two protonated forms, the nitro-protonated structure could be formed under mild excitation, explaining the results of the CA/NR experiments. It is also noteworthy that while nitrobenzene protonates on the nitro group, 2-, 3- and 4-nitropyridines are nitrogen bases. By and large, nitro derivatives of aromatic rings (obviously including heterocycles), B–NO_2 where B stands for the base, can be considered as bi-functional bases with highly interacting, competing basic centers.

These findings prompted us to investigate the gas-phase basicity of other nitro derivatives of structurally related compounds, namely the 2- and 3-nitro derivatives of pyrrole and furan and 5-nitro-1*H*-tetrazole. For the pyrrole derivatives, there is a possible competition between protonation on the the cycle, either on the NH group or on the carbon atoms, and protonation on the nitro group. Similarly, the furan derivatives can also be considered as bidentate bases, but in this case both basic sites would be oxygen atoms. On the other hand, in both cases the possible protonation on the carbon atoms of the ring should not be discarded, although *a priori* one should expect these centers to exhibit a lower intrinsic basicity than the oxygen of the nitro group or the heteroatoms of the ring. Finally, 5-nitro-1*H*-tetrazole should exhibit a lower intrinsic basicity of the ring nitrogens than nitropyrazoles and therefore it constitutes a good model to gain further insight into the competition between O and N protonation.

In principle, the experimental protonation site can be estimated by comparing the gas basicity, GB(B–NO_2), values predicted for B and NO_2 protonation by means of correlation analysis techniques. For example, in the case of B protonation, one can use the experimental GB of the parent compound (B–H) and an expression such as eqn. (1) for the gas-phase basicity of its derivatives, B–X, in terms of the corresponding Taft–Topsom parameters σ_α, σ_F and σ_{R+}, measuring respectively polarizability, field and resonance effects of the substituent X.[3]

$$\mathrm{GB(B{-}X)} - \mathrm{GB(B{-}H)} = +\rho_\alpha\sigma_\alpha(\mathrm{X}) + \rho_F\sigma_F(\mathrm{X}) + \rho_{R+}\sigma_{R+}(\mathrm{X}) \qquad (1)$$

This formalism has been successfully applied to the analysis of substituent effects on the gas basicity (GB) values of 2-, 3- and 4-substituted pyridines and 3- and 5-substituted pyrazoles.[4] In our case, GB(B–NO_2), assuming protonation on B could be determined by simply using the appropriate parameters for the nitro group.

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Table 1 Gas-phase basicities (GB) for nitro compounds B–NO$_2$[a]

R	GB[b]	σ_α[c]	σ_{R+}[c]	σ_F[c]
Me	172.5[d]	−0.35	−0.08	0.00
Et	175.2[d]	−0.49	−0.07	0.00
C_6H_5	183.9[d]	−0.81	−0.22	0.10
MeO	162.8[e,f]	−0.17	−0.38	0.25
NH_2	173.3[d] 173.0[e]	−0.16	−0.52	0.14
NMe_2	190.2[d] 189.8[e]	−0.44	−0.64	0.10
Cl	149.3[e]	−0.43	−0.17	0.45
H	155.7[e]	0	0	0
CN	141.3[e]	−0.46	0.00	0.60

[a] Protonation on the nitro group. [b] All values in kcal mol^{-1} (1 kcal mol^{-1} = 4.184 kJ mol^{-1}). [c] From ref. 3. [d] Experimental values from refs. 5 and 26. [e] Computed at the G2(MP2) level for protonation on the nitro group. [f] The experimental value taken from ref. 29 is 172.0 kcal mol^{-1} and corresponds to protonation on the methoxy oxygen. The corresponding G2(MP2)value (from this work) is 172.3 kcal mol^{-1}.

An expression of the form of eqn. (1), eqn. (2),

$$\mathrm{GB(B–NO_2)} = 156.8(\pm1.7) - 31.6(\pm3.1)\sigma_\alpha - 37.1(\pm3.2)\sigma_{R+} - 53.9(\pm3.2)\sigma_F \qquad (2)$$

(for which $n = 9$, $R^2 = 0.990$, SD = 2.0 kcal mol^{-1}) can be obtained for protonation on NO$_2$ of nitro compounds. The database for the latter is given in Table 1 and the ρ values for the various correlations are summarized in Table 2.

The GB values of the database span a range of *ca.* 50 kcal mol^{-1}. Substituents were chosen so as to reach near-orthogonality of the vectors σ_α, σ_{R+} and σ_F. Because of the scarcity of experimental values, we have used G2(MP2) calculations in order to increase the range of structural effects as well as to reduce the degree of colinearity of the descriptors. These calculations were also useful for the purpose of assessing the protonation site in the case of nitro compounds for which experimental data were available. The agreement between experimental and computational results is of the order of 1 kcal mol^{-1}. This justifies the mixing of purely experimental and purely computational values in the construction of eqn. (2).

We believe that this is the first systematic study of structural effects on the gas-phase basicity of nitro compounds. As we show below, the extension of this methodology to more complex systems is quite satisfactory.

Lastly, we mention that the absolute value of ρ_F in eqn. (2) is possibly the largest ever reported for any system. The values of ρ_α and ρ_{R+}, however substantial, are comparable to those found in the case of the protonation of α-substituted alcohols or α-substituted methyl ketones.

Very few descriptors are available for heterocyclic rings. Fortunately, σ_F and σ_{R+} values exist for 2-furyl (0.14, −0.35)[3] and 5-(1*H*)-tetrazolyl (0.65, −0.12).[3] Their σ_α values can be estimated as −0.63 (5/6 of the value for cyclohexyl).[3] With these values, summarized in Table 1, one can estimate the GB values for protonation on the nitro group of 2-nitrofuran and 5-nitro-(1*H*)-tetrazole.

Table 2 Application of the Taft–Topsom formalism to selected systems[a,b]

Compound	ρ_α	ρ_F	ρ_{R+}	GB(B–H)
4-X pyridines[c]	−5.4	−24.2	−29.1	214.7[e]
3-X pyridines[c]	−4.7	−25.7	−18.3	214.7[e]
3-X pyrazoles[c]	−9.4	−28.1	−17.4	205.7[e]
5-X pyrazoles[c]	−7.7	−27.4	−22.1	205.7[e]
R–NO$_2$[d]	−31.6	−37.1	−53.9	156.8[f]

[a] R. W. Taft and R. D. Topsom, *Prog. Phys. Org.Chem.* 1988, **16**, 1. [b] All values in kcal mol^{-1} (1 kcal mol^{-1} = 4.184 kJ mol^{-1}). [c] From ref. 4. [d] This work, see text. [e] Experimental value. [f] Computed through the correlation eqn. (2).

Table 3 Estimated gas-phase basicities for B–NO$_2$ bases[a]

B	GB(B)[b]	GB(NO$_2$)[c]
2-Furyl	164–170	191.6
5-(1*H*)-Tetrazolyl	170–176	163.2

[a] All values in kcal mol^{-1} (1 kcal mol^{-1} = 4.184 kJ mol^{-1}). See text. [b] Assuming ring protonation (any position). [c] Assuming protonation on the nitro group.

To our knowledge, substituent effects on the GBs and protonation sites of furan and 1*H*-tetrazole have not been investigated in detail. However, inspection of the data summarized in Table 2 and consideration of the σ_α, σ_F and σ_{R+} values for the nitro group (respectively −0.26, 0.65 and 0.00) indicate that a nitro group lowers the GB of the heterocycles by 14 to 20 kcal mol^{-1} with respect to the parent compound (for protonation on the heterocycle). We take these values as rough estimates of the effect of the nitro group on the GB values of other heterocycles (irrespective of the heterocyclic basic site). We summarize in Table 3 the GB values thus estimated for protonation on the ring and on the nitro group.

It is clear that within this crude model, ring and nitro group protonations are substantially favored in the cases of 5-nitro-(1*H*) tetrazole and 2-nitrofuran, respectively. Along this paper we shall provide further evidence that sustain these qualitative predictions as well as a rationalization of the different behavior of the nitro derivatives investigated upon protonation.

The experimental gas-phase proton affinities of pyrrole, tetrazole and furan were taken from the literature.[5] The gas-phase basicities of their nitro derivatives are not known, and in this work we have measured that of 2-nitrofuran. Unfortunately, 5-nitro-1*H*-tetrazole is a shock-sensitive energetic material that prevents its handling in normal FT-ICR experiments.

Experimental

The experimental determination of the gas-phase basicity of 2-nitrofuran (**2NF**), GB(**2NF**), was carried out by means of Fourier transform ion cyclotron resonance mass spectrometry[6–8] using a modified Bruker CMS47 mass spectrometer.[9] Relevant features of this instrument and its modifications are given in refs. 9 and 10. The field strength of its superconducting magnet, 4.7 T, allows the monitoring of ion-molecule reactions for relatively long periods of time.

GB(**2NF**) is defined as GB(**2NF**) = $\Delta_r G^\circ_m$(3):

$$\mathbf{2NF}\text{–}H^+(g) \rightarrow \mathbf{2NF}(g) + H^+ \qquad (3)$$

and is determined from the position of equilibrium (4):

$$2NF(g) + B_{ref}H^+(g) \xrightleftharpoons{K_p} 2NFH^+(g) + B_{ref}(g) \qquad (4)$$

where B$_{ref}$ is a reference compound of known basicity.

Then eqn. (5) holds:

$$\Delta GB = GB(B_{ref}) - GB(\mathbf{2NF}) = -RT\ln K_p \qquad (5)$$

Working conditions were as follows: nominal pressures of B$_{ref}$ and **2NF** were in the range 1–5 × 10^{-7} mbar. In some experiments argon was added up to total pressures of 1–2 × 10^{-6} mbar.

Reagents, introduced into the high-vacuum section of the instrument, were subject to electron ionization (at nominal energies of 14–18 eV). The protonation was obtained by chemical ionization, proton sources being the ionic fragments of

Table 4 Experimental results[a] pertaining to the determination of the gas-phase basicity of 2-nitrofuran (**2NF**)

Reference	GB($\mathrm{B_{ref.}}$)	ΔGB	GB
n-BuSH	184.33	+0.78	183.55
n-BuCHO	182.97	−0.42	183.39
i-PrSH	184.76	+1.47	183.29
			183.4[b]

[a] All values in kcal mol^{-1} (1 kcal mol^{-1} = 4.184 kJ mol^{-1}). [b] Average value

$\mathrm{B_{ref}}$. The ratio of the relevant pressures, $P(\mathbf{2NF})/P(\mathrm{B_{ref}})$ was modified within the widest possible limits. It was also established by means of ion selection experiments that the same constant ratio of the intensities($P_{\mathrm{2NFH+}}/P_{\mathrm{B_{ref}H+}}$) was reached with or without ion selection This ratio was also independent of the addition of argon.

The pressure readings for the neutral reactants determined by the Bayard–Alpert gauge of the FT-ICR spectrometer were corrected with the gauge sensitivity[11] using the average molecular polarizability α(ahc) calculated according to Miller.[5]

The different $\mathrm{B_{ref}}$, their GB values (taken from ref. 12), and the corresponding ΔGB are given in Table 4. They lead to an average value of 183.4 Kcal mol^{-1} for GB(**2NF**).

Computational details

Methodology

The geometries of the different neutral compounds and their protonated species have been optimized by means of the B3LYP density functional theory approach, as implemented in the Gaussian-98 series of programs,[13] together with a 6-31G* basis set expansion. The same level of theory has been used to obtain the harmonic vibrational frequencies and to estimate the zero point energy (ZPE), which was scaled by the empirical factor 0.9806.[14] The B3LYP approach combines Becke's three-parameter nonlocal hybrid exchange potential[15] with the non-local correlation functional of Lee, Yang and Parr.[16] In general, B3LYP/6-31G* optimized geometries are in fairly good agreement with experimental values,[17–23] and the harmonic vibrational frequencies are closer to experiment than those obtained by using other correlated methods such as MP2.[24,25] The final energies were obtained in single-point calculations carried out at the B3LYP/6-311+G(2df,2p) level and also within the framework of the G2(MP2) theory,[26] but using the aforementioned B3LYP optimized geometries rather than the MP2/6-31G* ones used in the G2(MP2) standard procedure.[26] Also, the ZPE correction used was that obtained at the B3LYP/6-31G* level. The corresponding proton affinities were evaluated by including the thermal corrections and the Δ(*PV*) term evaluated at the B3LYP/6-31G* level and for a temperature of 298.2 K. The entropy changes evaluated at the same level were used to estimate the corresponding gas-phase basicities from these calculated proton affinities.

Assessment of the theoretical model

In order to asses the reliability of our theoretical model, in particular for those nitro derivatives for which no experimental values are available, we have calculated the proton affinities of some derivatives, such as nitromethane (**NMe**), nitroethane (**NEt**), nitrobenzene (**NB**) and methyl nitrate (**MeN**), which unequivocally protonate on the nitro group. To this set we have added some unsubstituted five-membered rings such as pyrrole (**P**), pyrazole (**Pz**) and imidazole (**Im**), whose gas-phase proton affinities are also accurately known.[5] As illustrated in Fig. 1, all these compounds lie on the same linear correlation between experimental and theoretical values. Furthermore, the slope and the correlation coefficient are both close to unity. More importantly, when this correlation is used to estimate the "experimental" gas-phase proton affinities of 3-nitrofuran (**3NF**), 2-nitropyrrole (**2NP**) and 3-nitropyrrole (**3NP**), the values obtained differ from the calculated ones reported in Tables 5 and 6 by less than 1 kcal mol^{-1} (*vide infra*).

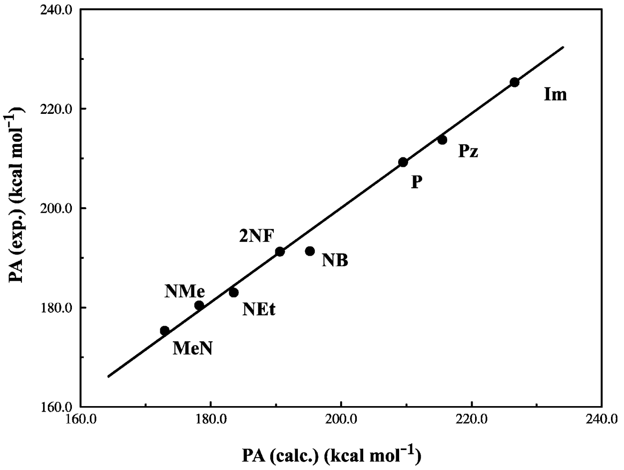

Fig. 1 Linear correlation between experimental and calculated proton affinities of some nitro derivatives and some representative five-membered ring bases.

Results and discussion

Pyrrole and nitropyrrole derivatives

The optimized geometries of pyrrole (**P**), 2-nitro (**2NP**) and 3-nitropyrrole (**3NP**) are given in Fig. 2. This figure also contains the structures of the most stable ring-protonated and nitro-protonated forms. The structures of the remaining protonated species are available from the authors upon request. The total energies and the calculated proton affinities are summarized in Table 5.

The first conspicuous fact is that pyrrole protonation is favored at the carbon atom directly bound to the heteroatom. Furthermore, assuming that protonation takes place on C2 the agreement between calculated and experimental proton affinity[27] and basicity is excellent. Conversely, both the **2NP** and the **3NP** nitro derivatives protonate preferentially on the oxygen of the nitro group. It is worth noting that in both cases the estimated intrinsic basicity of this group is rather similar to that of nitrobenzene, and higher than that of nitromethane or nitroethane, which were taken as suitable reference systems (see Table 1). Hence, there are two opposite effects: on the one hand there is an enhanced basicity of the nitro group due to the resonance interaction with the aromatic system, similar to that observed in nitrobenzene, and on the other hand, the withdrawing effect of the nitro group results in a decrease of the intrinsic basicity of the different atoms of the ring of about 20 kcal mol^{-1}.

Furan and nitrofuran derivatives

The optimized geometries of furan (**F**), 2-nitrofuran (**2NF**), 3-nitrofuran (**3NF**) and their protonated forms are given in Fig. 3. The information on protonated forms is restricted to the most stable ring- and nitro-protonated species. The remaining ones are available from the authors upon request. The corresponding proton affinities and gas-phase basicities are summarized in Table 6. As it was found for pyrrole the parent compound behaves as a carbon base, the protonation at C2 being favored over the protonation at the oxygen atom

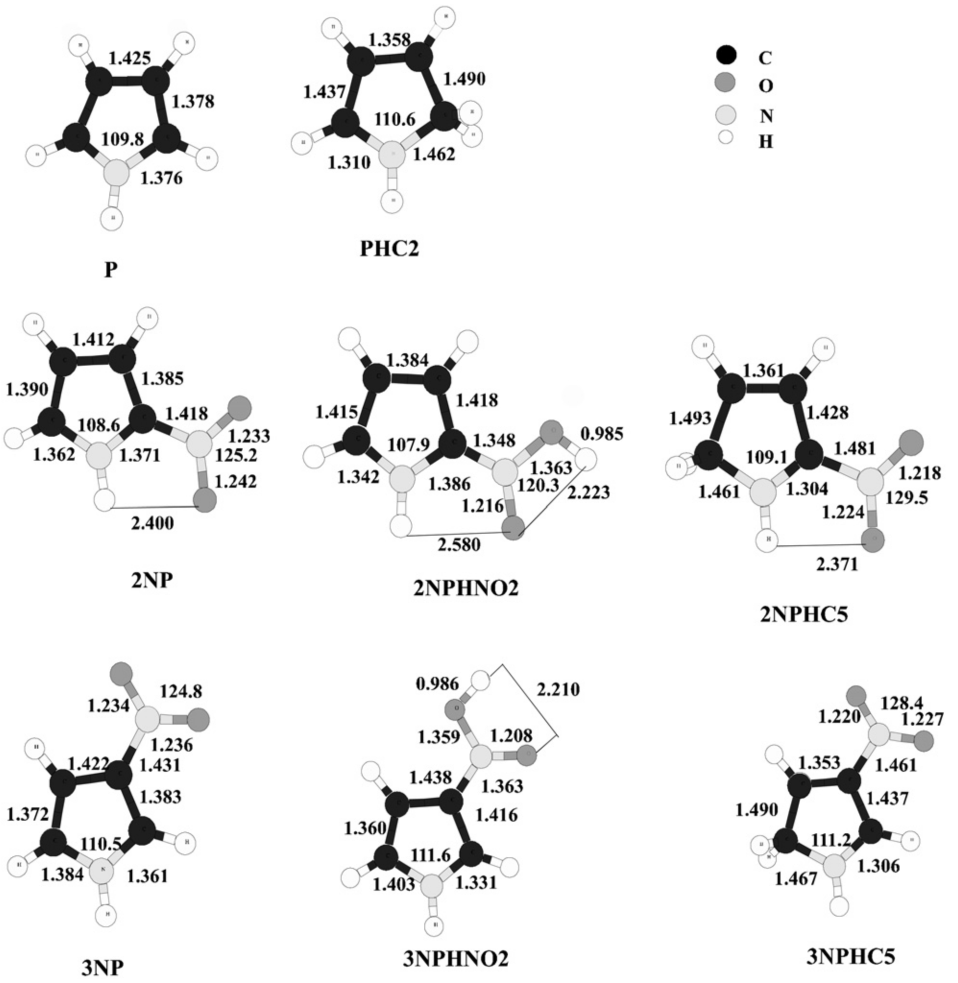

Fig. 2 B3LYP/6-31G* optimized geometries of pyrrole, 2-nitropyrrole, 3-nitropyrrole and their most stable ring- and nitro-protonated species. Bond lengths are in Å and bond angles in degrees.

or at C3. Quite surprisingly, in this case, the calculated values assuming protonation on C2, both at the B3LYP/6-311+G(3dfd,2p) and G2(MP2) levels, overestimate the experimental values[27] by about 3–4 kcal mol^{-1}.

Following similar arguments to those outlined above for the case of pyrrole one can anticipate that both nitro derivatives should protonate preferentially at the oxygen atoms of the nitro group. In this particular case the agreement between

Table 5 Total energies (E, hartrees), zero point energies (ZPE, hartrees) and entropy values (S, cal mol^{-1} K^{-1}) for the neutral and the protonated forms of pyrrole and its 2-nitro and 3-nitro derivatives. PA and GB are the corresponding proton affinities and gas-phase basicities (in kcal mol^{-1}), respectively

	B3LYP/6-31G*		B3LYP/6-311+G(3df,2p)			G2(MP2)			Exptal	
System	ZPE	S	E	PA	GB	E	PA	GB	PA	GB
P	0.080964	66.011	−210.246169			−209.772748				
PHN1	0.093926	66.630	−210.557262	188.6	180.7	−210.074066	190.6	182.7		
PHC2	0.093540	66.541	−**210.590128**	**209.5**	**201.5**	−**210.102901**	**208.7**	**200.8**	**209.2**	**201.7**
PHC3	0.092750	66.963	−210.580953	204.2	196.5	−210.095924	204.2	196.6		
2NP	0.084170	79.311	−414.828430			−414.047724				
2NPHN1	0.096244	81.274	−415.108220	169.7	162.2	−414.321751	173.7	166.2		
2NPHNO2	0.095991	80.419	−**415.159426**	**202.0**	**194.2**	−**414.361397**	**198.5**	**190.8**	–	–
2NPHC3	0.094492	81.587	−415.124055	180.8	173.4	−414.336803	183.1	175.7		
2NPHC4	0.094924	80.827	−415.130892	184.7	177.1	−414.343168	187.1	179.4		
2NPHC5	0.095149	81.587	−415.133172	186.0	178.6	−414.344521	187.9	180.5		
3NP	0.084249	79.735	−414.826766			−414.047346				
3NPHN1	0.096090	81.686	−415.104055	168.3	160.8	−414.318899	172.1	164.6		
3NPHC2	0.095739	81.796	−415.136773	189.0	181.5	−414.348359	190.6	183.1		
3NPHNO2	0.096374	80.185	−**415.160441**	**203.4**	**195.4**	−**414.363589**	**200.0**	**192.1**	–	–
3NPHC4	0.095050	81.682	−415.129130	184.7	177.2	−414.342195	186.7	179.2		
3NPHC5	0.095717	81.327	−415.138169	189.9	182.2	−414.348830	190.8	183.2		

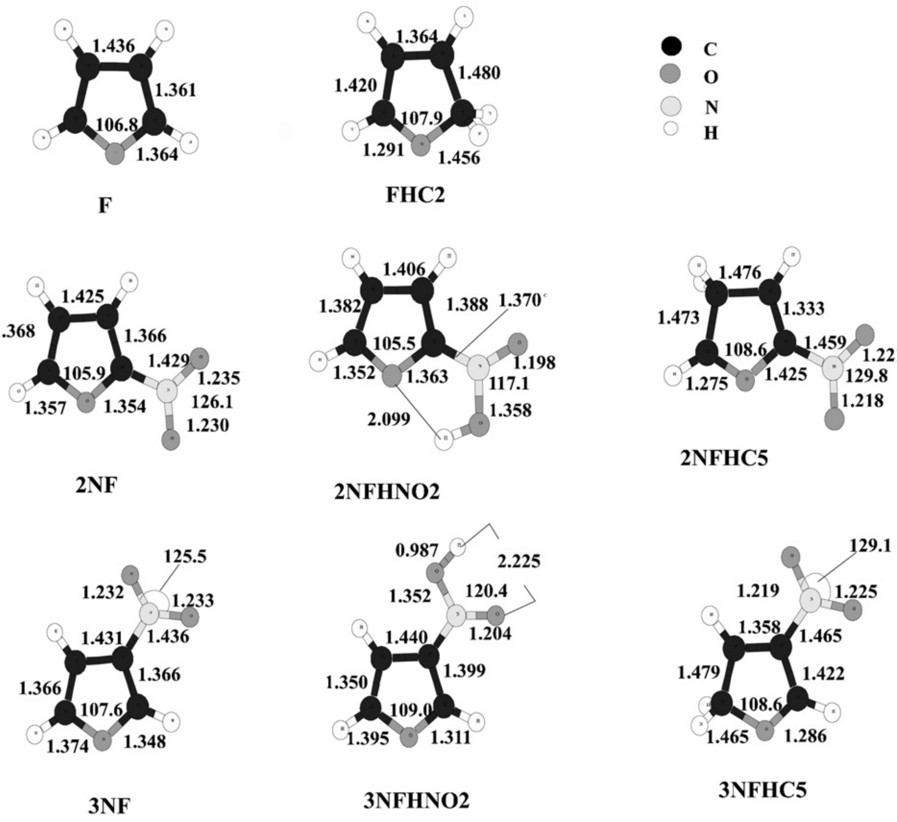

Fig. 3 B3LYP/6-31G* optimized geometries of furan, 2-nitrofurane, 3-nitrofurane and their most stable ring- and nitro-protonated species. Bond lengths are in Å and bond angles in degrees.

calculated values at the B3LYP/6-311+G(3dfd,2p) level and the experimental ones is very good, while the G2(MP2) values underestimate the experimental data. In any case, in view of the gap between the proton affinity for protonation on the nitro group and the proton affinities for protonation on the ring, one may safely conclude that both nitrofuran derivatives protonate on the substituent. It is of interest that GB(**2NF**) as estimated by the Taft–Topsom model (see Table 3) is in respectable agreement with the experimental datum (see Table 4) and the G2(MP2) calculations (see Table 6). We are not aware of other instances wherein substituent descriptors for heterocycles had been used for predictive purposes in gas-phase ion chemistry. Actually, although substituent effects on the gas-phase reactivity of heterocyclic systems such as pyridines[5] and quinuclidines[28] are available, we are not aware, however, of their being used for the determination of the electronic parameters for these heterocycles as substituents.

This result confirms the broad scope and usefulness of this correlation analysis method. Furthermore, the (scarce) information so far available for heterocycles[3] was mostly intended

Table 6 Total energies (E, hartrees), zero point energies (ZPE, hartrees) and entropy values (S, cal mol^{-1} K^{-1}) for the neutral and the protonated forms of furan and its 2-nitro and 3-nitro derivatives. PA and GB are the corresponding proton affinities and gas-phase basicities (in kcal mol^{-1}), respectively

	B3LYP/6-31G*		B3LYP/6-311+G(3df,2p)			G2(MP2)			Exptal	
System	ZPE	*S*	*E*	PA	GB	*E*	PA	GB	PA	GB
F	0.068795	63.721	−230.105277			−229.626768				
FHO1	0.079277	66.916	−230.380306	167.8	160.7	−229.890792	167.5	160.4		
FHC2	0.080731	66.120	**−230.428324**	**196.8**	**189.5**	**−229.935032**	**195.0**	**187.6**	**192.0**	**184.3**
FHC3	0.079173	66.586	−230.408319	185.4	178.1	−229.918694	184.9	177.7		
2NF	0.071589	79.229	−434.677096			−433.892501				
2NFHO1	0.080170	85.240	−434.930485	155.6	149.3	−434.137266	155.6	149.3		
2NFHNO2	0.083106	79.976	**−434.989656**	**190.6**	**182.7**	**−434.188450**	**187.4**	**179.5**	**191.2**	**183.4**
2NFHC3	0.080464	77.685	−434.943814	163.2	153.3	−434.152416	164.5	154.6		
2NFHC4	0.081162	81.657	−434.948529	166.1	158.8	−434.156192	167.3	159.9		
2NFHC5	0.082064	77.087	−434.965570	175.7	165.7	−434.170870	175.9	166.0		
3NF	0.071734	79.314	−434.679196			−433.895523				
3NFHO1	0.081356	81.986	−434.924369	149.7	142.4	−434.132375	150.5	143.3		
3NFHC2	0.082640	82.348	−434.969692	177.2	170.0	−434.175367	177.4	170.2		
3NFHNO2	0.083427	79.946	**−434.994007**	**191.8**	**184.0**	**−434.193231**	**188.5**	**180.6**	–	–
3NFHC4	0.081352	81.856	−434.951592	166.7	159.4	−434.160087	167.8	160.5		
3NFHC5	0.082682	81.250	−434.971414	178.2	170.7	−434.176001	177.7	170.2		

for QSAR studies relevant to biological and health sciences. Our results indicate that both gas-phase experiments and quantum mechanics can be used to generate these important data.

1*H*-Tetrazole and 5-nitro-1*H*-tetrazole

The optimized geometries of 1*H*-tetrazole (**T**) and 5-nitro-1*H*-tetrazole (**NT**) and their most stable ring- and nitro-protonated species are given in Fig. 4. The corresponding proton affinities and gas-phase basicities are summarized in Table 7.

Our calculations show that 1*H*-tetrazole protonates preferentially on N4, although the protonated species resulting from protonation at N3 is estimated to be only 1 kcal mol^{-1} less stable than the N4-protonated species. In this case the comparison with the available experimental data does not solve this dichotomy because, on the one hand the stability difference between both protonated species is rather low and on the other hand the experimental value was obtained many years ago by Taft and coworkers[3] and has never being anchored with regards to the new basicity scale, so that it can be affected by some error. In any case, the agreement with the calculated value is reasonably good. It is also worth noting that protonation on N1 leads to a N1–N2 bond cleavage. The important result is that the corresponding open structure is predicted to be only 4 kcal mol^{-1} higher in energy than the N4-protonated form and that, as we shall discuss later, for the nitro derivatives it becomes the global minimum of the potential energy surface. Also, protonation on C5 leads to a N2–N3 bond fission, but in this case the corresponding open cation is much less stable than the other protonated species.

As it was found for pyrrole and furan, nitro substitution leads to a roughly constant decrease of about 15 kcal mol^{-1} of the intrinsic basicity of all positions of the ring. It can be observed, however, that this effect is slightly higher for the nitrogen atom (N4) in the *ortho* position with respect to the substituted carbon than for N3. The consequence is that while for the unsubstituted parent compound the protonation on N4 was slightly favored with respect to the protonation on N3, for the nitro derivative it is the other way around. Also, as it was found for the unsubstituted parent compound, protonation on N1 yields a non-cyclic cation, namely **NTHN1**, which is predicted to be the most stable protonated species. The enhanced stability of this open form is likely due to two concomitant factors. On the one hand, there is the formation of an O···H–N intramolecular hydrogen bond between the NH_2 group formed upon protonation and the nitro group, which is favored by the ring opening, and on the other hand there is a more favorable electrostatic interaction between the terminal nitrogen atom of the NNN moiety and one of the hydrogen atoms of the NH_2 group.

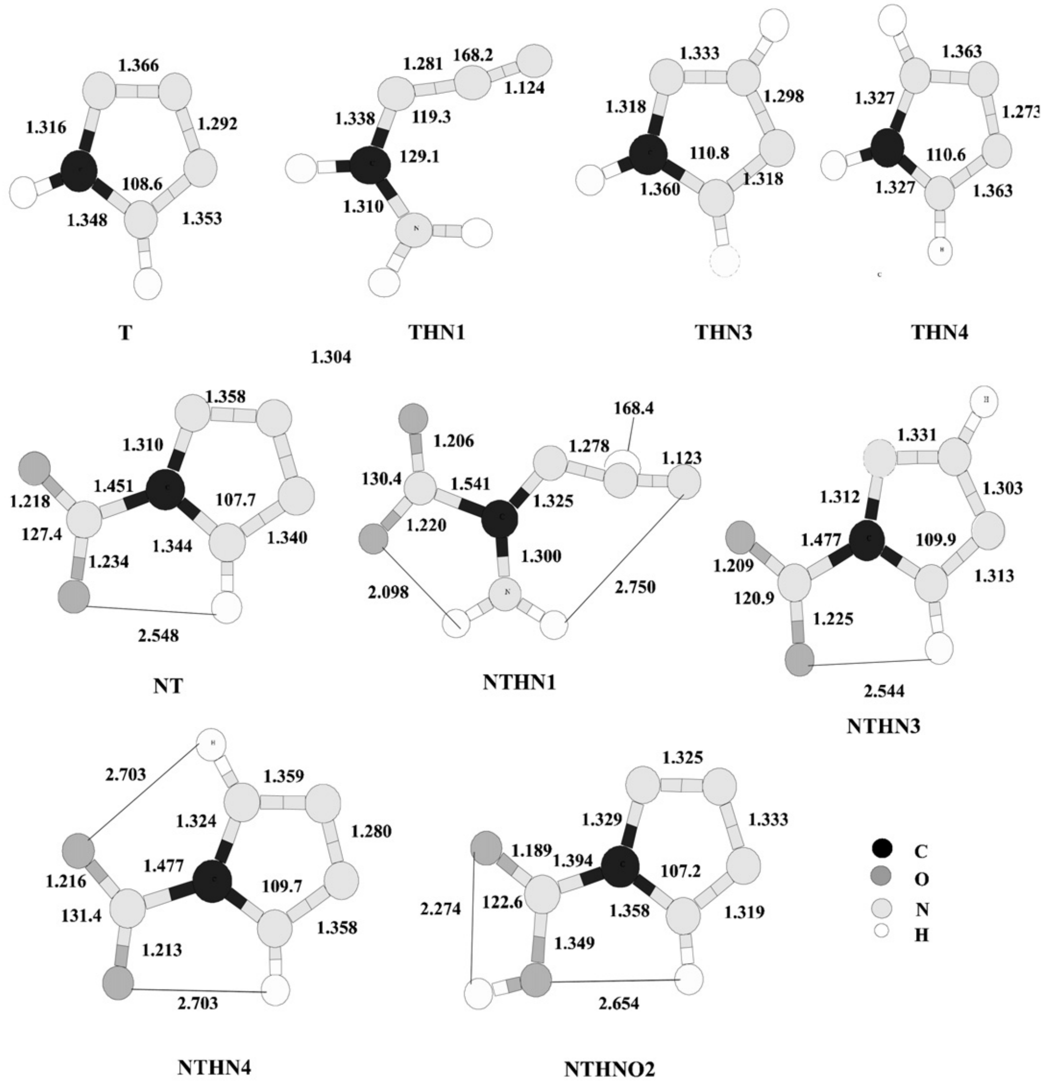

Fig. 4 B3LYP/6-31G* optimized geometries of 1*H*-tetrazole, 4-nitro-1*H*-tetrazole and their most stable ring- and nitro-protonated species. Bond lengths are in Å and bond angles in degrees.

Table 7 Total energies (E, hartrees), zero point energies (ZPE, hartrees) and entropy values (S, cal mol^{-1}) for the neutral and the protonated forms of 1H-tetrazole and its 4-nitro derivative. PA and GB are the corresponding proton affinities and gas-phase basicities (in kcal mol^{-1}), respectively

	B3LYP/6-31G*		B3LYP/6-311+G(3df,2p)			G2(MP2)			Exptal	
System	ZPE	S	E	PA	GB	E	PA	GB	PA	GB
T	0.046003	64.261	−258.344380			−257.870772				
THN1	0.057035	70.258	**−258.675362**	**203.1**	**196.8**	−258.181010	**197.0**	**190.7**		
THN2	0.058443	64.922	−258.651057	186.2	178.3	−258.162254	184.5	176.6		
THN3	0.060069	64.285	**−258.677070**	**201.4**	**193.3**	**−258.187293**	**200.1**	**192.0**	**198.2**	**190.2**
THN4	0.059209	64.528	**−258.677381**	**202.2**	**194.2**	**−258.188852**	**201.1**	**193.1**		
THC5	0.055225	68.169	−258.592090	151.7	144.8	−258.110120	152.3	145.4		
NT	0.048359	78.769	−462.901594			−462.123848				
NTHN1	0.058329	84.876	**−463.214320**	**192.3**	**186.0**	**−462.418705**	**186.5**	**181.1**	–	–
NTHN2	0.060167	79.864	−463.184199	171.6	163.8	−462.393387	170.8	163.0		
NTHN3	0.061743	79.311	**−463.210057**	**186.7**	**178.8**	**−462.418070**	**186.1**	**178.3**		
NTHN4	0.060751	79.788	−463.207417	185.8	178.0	−462.416663	185.2	177.6		
NTHNO2	0.059324	79.652	−463.173851	165.6	157.8	−462.380504	162.7	154.9		

Also importantly, the estimated intrinsic basicity of the nitro group is smaller than that of nitromethane or nitroethane. In other words, while the attachment of a nitro substituent to benzene, pyrrole or furan implies an enhancement of the intrinsic basicity of the nitro group, its attachment to a tetrazole ring implies a large decrease of its intrinsic basicity, because in this case, due to the accumulation of nitrogen atoms, the five-membered ring does not behave as an electron donor with respect to the nitro group, as it is the case in benzene or in pyrrole and furan. This is actually reflected in the C–NO_2 bond distance, which in the nitrotetrazole is larger than in the analogous nitropyrrole or nitrofuran derivatives. Also, the charge at the oxygen lone pairs, obtained by locating the maxima of the Laplacian of the charge density, are slightly smaller in 5-nitro-1H-tetrazole (0.23 e au^{-3}) than in 2-nitropyrrole and 2-nitrofuran (0.26 e au^{-3}). Also, the O–H bond formed upon protonation is weaker when the base is 5-nitro-1H-tetrazole than when the base is 2-nitropyrrole or 2-nitrofuran, reflecting the smaller electron donor ability of the nitro group of the former. Indeed, not only the O–H bond in **NTHNO2** is longer than in **NFHNO2** and **NPHNO2**, but also the charge density at the corresponding bond critical point is smaller (by 0.008 e au^{-3}), as well as the O–H stretching frequency (3528 cm^{-1} *vs.* 3580 and 3592 cm^{-1}, respectively). The main consequence is that while the nitro derivatives of pyrrole and furan protonate preferentially on the nitro group, the protonation of 5-nitro-1H-tetrazole should take place preferentially on the azolic ring.

A second important finding is that among the different protonated species arising from ring protonation of **NT**, the two associated with protonation on N1 and N3, namely **NTHN1** and **NTHN3**, are predicted to be nearly degenerate at the G2(MP2) level of theory. However, since as we have mentioned above N1 protonation leads to N1–N2 bond cleavage, the corresponding open structure is entropically favored. This means that very likely, under normal experimental conditions in ICR experiments, the protonated form observed would be complex **NTHN1** rather than the cyclic cation **NTHN3**. Our theoretical estimates allow us to predict that at 298 K protonated 5-nitrotetrazole should be an equilibrium mixture of **THN3** (82.7%), **THN4** (12.9%) and **THN1** (1.4%). Unfortunately, as we have already indicated in the introduction, the explosive nature of this compound prevents these measurements from being carried out.

It is important to indicate that these results are also consistent with the fact that while for 4-nitropyrazole ring protonation is only favored by 6 kcal mol^{-1} over nitro protonation, in the case of 5-nitro-1H-tetrazole this gap is 4 times larger, as a consequence of the aforementioned basicity dampening of the nitro group in this latter compound.

Conclusions

Our results indicate that although pyrrole and furan behave as carbon bases in the gas phase, their nitro derivatives protonate preferentially on the nitro group. This is due to two concomitant effects: a dampening of the intrinsic basicity of the ring atoms upon substitution and an enhancement of the basicity of the nitro substituent when attached to pyrrole or furan moieties. Conversely, both 1H-tetrazole and its 5-nitro derivative protonate preferentially on the ring, because the intrinsic basicity of the nitro group is significantly dampened when the group is attached to a tetrazolic ring.

Also importantly, for the nitro derivative the most stable protonated species corresponds to an open structure formed by protonation at N1, which is followed by a N1–N2 bond cleavage. This non-cyclic structure is entropically favored and therefore we may conclude that it should be the one observed in ICR measurements.

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References

1 C. Foces-Foces, A. L. Llamas-Saiz, M. Menéndez, N. Jagerovic and J. Elguero, *J. Phys. Org. Chem.*, 1997, **10**, 637.

2 J.-L. M. Abboud, R. Notario, M. Yanez, O. Mo, R. Flammang, N. Jagerovic, I. Alkorta and J. Elguero, *J. Phys. Org. Chem.*, 1999, **12**, 787.

3 C. Hansch, A. Leo and R. W. Taft, *Chem. Rev.*, 1991, **91**, 165.

4 J.-L. M. Abboud, P. Cabildo, T. Cañada, J. Catalán, R. M. Claramunt, J. L. G. de Paz, J. Elguero, H. Homan, C. Toiron and G. I. Yranzo, *J. Org. Chem.*, 1992, **57**, 3938.

5 K. J. Miller, *J. Am. Chem. Soc.*, 1990, **112**, 8533.

6 A. G. Marshall, C. L. Hendrickson and G. S. Jackson, *Mass Spectrom. Rev.*, 1998, **17**, 1.

7 J.-L. M. Abboud and R. Notario, in *Energetics of Stable Molecules and Reactive Intermediates*, ed. M. E. Minas da Piedade,

NATO ASI Series, Kluwer Academic Publisher, Dordrecht, 1999, p. 281.

8 J.-F. Gal, P.-C. Maria and E. D. Raczynska, *J. Mass Spectrom.*, 2001, **36**, 699.

9 F. H. Laukien, M. Allemann, P. Bischofberger, P. Grossmann, H. P. Kellerhals and P. Kofel, in *Fourier Transfrom Mass Spectrometry. Evolution, Innovation and Applications*, ed. M. V. Buchanan, American Chemical Society, Washington, DC, 1987, ch. 5, p. 81.

10 J. L. M. Abboud, M. Herreros, R. Notario, M. Esseffar, O. Mo and M. Yanez, *J. Am. Chem. Soc.*, 1996, **118**, 1126.

11 J. E. Bartmess and R. M. Giorgiadis, *Vacuum*, 1983, **3**, 149.

12 E. P. L. Hunter and S. G. Lias, *J. Phys. Chem. Ref. Data*, 1998, **27**, 413.

13 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. J. A. Montgomery, R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, J. L. Andres, C. Gonzalez, M. Head-Gordon, E. S. Replogle and J. A. Pople, Gaussian 98, Rev A3, Gaussian, Inc., Pittsburgh PA, 1999.

14 A. P. Scott and L. Radom, *J. Phys. Chem.*, 1996, **100**, 16 502.

15 A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 1372.

16 C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B: Condens. Matter*, 1988, **37**, 785.

17 F. Sim, A. St-Amant, I. Papai and D. R. Salahub, *J. Am. Chem. Soc.*, 1992, **114**, 4391.

18 K. Kim and K. D. Jordan, *J. Phys. Chem.*, 1994, **98**, 10 089.

19 C. W. Bauschlicher, *Chem. Phys. Lett.*, 1995, **246**, 40.

20 A. L. Llamas-Saiz, C. Foces-Foces, O. Mo, M. Yanez, E. Elguero and J. Elguero, *J. Comput. Chem.*, 1995, **16**, 263.

21 A. M. Mebel, K. Morokuma and M. C. Lin, *J. Chem. Phys.*, 1995, **103**, 7414.

22 J. A. Montgomery, Jr., M. J. Frisch, J. W. Ochterski and G. A. Peterson, *J. Chem. Phys.*, 1999, **110**, 2822.

23 L. A. Curtiss, P. C. Redfern, K. Raghavachari and J. A. Pople, *J. Chem. Phys.*, 2001, **114**, 108.

24 P. J. Stephens, F. J. Devlin, C. F. Chabalowski and M. J. Frisch, *J. Phys. Chem.*, 1994, **98**, 11 623.

25 M. W. Wong, *Chem. Phys. Lett.*, 1996, **256**, 391.

26 L. A. Curtiss, K. Raghavachari and J. A. Pople, *J. Chem. Phys.*, 1993, **98**, 1293.

27 *NIST Chemistry Webbook. Standard Reference Database Number 69*, July 2001 release.

28 W. Adcock, F. Anvia, G. Butt, A. Cook, P. Duggan, C. A. Grob, S. Marriott, J. Rowe, M. Taagepera, R. W. Taft and R. W. Topsom, *J. Phys. Org. Chem.*, 1991, **4**, 353.

29 F. Cacace, M. Attinà, M. De Petris and M. Speranza, *J. Am. Chem. Soc.*, 1994, **116**, 6413.