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High basicity of tris-(tetramethylguanidinyl)-phosphine imide in the gas phase and acetonitrile—a DFT study

B. Kovačević[a,*] and Z. B. Maksić[a,b]

[a] *Quantum Chemistry Group, Department of Organic Chemistry and Biochemistry, Ruđer Bošković Institute, Bijenička c. 54, 10000 Zagreb-HR, Croatia*

[b] *Division of Physical Chemistry, Faculty of Science and Mathematics, The University of Zagreb, Horvatovac 102a, 10000 Zagreb-HR, Croatia*

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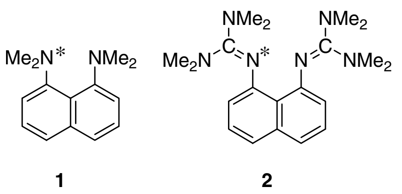
Abstract—It is shown by reliable density functional theory (DFT) calculations that compounds **4** and **6** are very powerful neutral organic superbases as evidenced by the calculated proton affinities in the gas phase 305.4 kcal mol^{-1} (44.8) and 287.8 kcal mol^{-1} (37.8), respectively, and the corresponding calculated pK_a values in acetonitrile given within parentheses.

Strong non-ionic bases and superbases have been the focus of wide attention since the pioneering synthesis of the first proton sponge by Alder and co-workers.[1,2] It was found that superbasicity was an inherent property of several families of compounds like guanidines,[3–6] phosphazenes,[7–11] quinodiimines and related systems,[12] as well as extended 2,5-dihydropyrrolimines.[13] Alder's paradigmatic 1,8-bis(dimethylamino)naphthalene (DMAN) **1** (Scheme 1) system has been the basis for a number of derivatives.[14–16] The intramolecular hydrogen bonding (IHB) motif, utilized first by Alder, was successfully employed in designing powerful neutral organic superbases, being particularly effective in various multiple IHB patterns.[17,18] Recently, extensions of Alder's DMAN were introduced by replacing the NMe_2 groups in **1** by guanidino and phosphazeno functions in TMGN **2** and HMPN **3**, respectively, thus leading to substantial enhancement of basicity.[19–21] We report here on the considerable increase in basicity upon replacement of the NMe_2 in phosphazene bases **3** and **5** by guanidino groups yielding superbases **4** and **6**, respectively, and compare their properties with Me-P_4 superbase **7** (Fig. 1). We also studied the proton affinities (PAs) in the gas phase and pK_a values in acetonitrile (MeCN) and offer a rationalization of the basicity by employing triadic analysis.[22]



Scheme 1.

The intrinsic gas phase proton affinities were obtained using the B3LYP/6-311+G(2df,p)//B3LYP/6-31G*

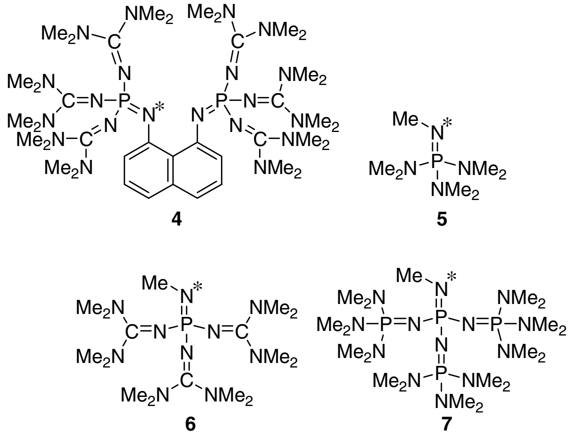


Figure 1. Schematic representation of the examined phosphazene bases, the most basic site is denoted by an asterisk.

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[*] Corresponding author. Tel.: +385 1 4561117; fax: +385 1 4561118; e-mail: boris@spider.irb.hr

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Table 1. The gas phase proton affinities $PA(gp)_N$ of compounds **1**–**7** and their triadic components (in kcal mol^{-1})[a]

Compound	$PA(gp)_N$	$(IE)_n^{Koop}$	$E(ei)_{rex}^{(n)}$	$(BAE)_{\alpha}^{\bullet +}$	pK_a (MeCN)
1	245.1	$(199.8)_3$	54.4	76.9	18.2[b]
2	263.8	$(207.2)_4$	74.3	83.1	25.1[c]
3	273.9	$(201.9)_3$	80.9	81.3	29.9[d]
4	305.4	$(184.7)_3$	86.3	90.0	44.8
5	260.7	$(215.9)_1$	63.9	99.0	28.5
6	287.3	$(197.3)_1$	75.6	95.3	37.8
7	296.4	$(190.3)_1$	78.1	94.8	42.2

[a] We denote HOMO by $n = 0$ and lower lying MOs by $n > 0$ (see text).

[b] Ref. 23.

[c] Refs. 19,20.

[d] Ref. 21.

method employing the formulae described elsewhere.[10] Perusal of the results given in Table 1 reveals a steady increase in the PA along the series of closely related compounds **1**–**4** culminating with PA (**4**) = 305.4 kcal mol^{-1}, which is the highest calculated value obtained so far. It enters the range of deprotonation energies of strong mineral superacids, which is important, if spontaneous proton transfer reactions are considered. Another interesting series of molecules is provided by systems **5**, **6** and **7**, with corresponding PAs of 260.7, 287.3 and 296.4 kcal mol^{-1}. Whereas **5** is a base of moderate, but respectable basicity, compounds **6** and **7** should be very strong superbases approaching the upper limit of 300 kcal mol^{-1}.

Interpretation of the calculated PAs can be conveniently obtained using formula (1):[22]

$$(PA)_{\alpha} = -(IE)_n^{Koop} + E(ei)_{rex}^{(n)} + (BAE)_{\alpha}^{\bullet +} + 313.6\ \text{kcal mol}^{-1} \qquad (1)$$

where $-(IE)_n^{Koop}$ refers to the *n*th Hartree–Fock orbital energy ε_n. The negative value of the latter is equal to the *n*th ionization energy given within Koopmans' approximation, that is, in the sudden approximation with underlying clamped nuclei and the frozen electron density picture. Hence, it mirrors the initial state effect. The bond association energy $(BAE)_{\alpha}^{\bullet +}$ reflects the energy released upon formation of a new X_{α}–H bond between the X_{α} atom of the molecular cation obtained by ionization of the initial base and the hydrogen atom, produced by capture of the electron from the neutral base by the incoming proton. It describes, therefore, the final state. Their interplay is given by the relaxation energy $E(ei)_{rex}^{(n)}$, which originates from the reorganization of the nuclei and electrons during the ionization event occurring in real time. It is obtained by

$$E(ei)_{rex}^{(n)} = (IE)_n^{Koop} - (IE)_1^{ad} \qquad (2)$$

where the $(IE)_1^{ad}$ denotes the first adiabatic ionization energy. Consequently, $E(ei)_{rex}^{(n)}$ represents the intermediate stage in the protonation process. It should be noted that the *n*th Hartree–Fock molecular orbital (HF MO) is a particular molecular orbital, which is changed the most by protonation. Specifically, in this case, the lone pair MO of the imino group, denoted by an asterisk in Figure 1, directly participates in the formation of a new $(N–H)^+$ bond. It should be mentioned that Koopmans' ionization energy is computed using the HF/6-311+G(2df,p)//B3LYP/6-31G* model. The calculated gas phase proton affinities of compounds **1**–**7** and their partitioning into triadic components are given in Table 1. It should be pointed out that P=N bonds are not double bonds in their usual meaning, since the imino nitrogen has two lone pairs: one perpendicular to the Me-N-P fragment and the other in this plane. The MO describing the former is the HOMO, which is denoted by $n = 0$. The latter lone pair is the protonated one with the corresponding MO signified by $n = 1$. Inspection of the results reveals that the increase in PA along compounds **5**–**7** is a consequence of a decrease in the $(IE)_1^{Koop}$ term and an increase in the relaxation energy $E(ei)_{rex}^{(n)}$. Employing **5** as a reference system, triadic analysis readily provides the relative values:

$$PA(\mathbf{n})_{\alpha} - PA(\mathbf{5})_{\alpha} = [-\Delta(IE^{Koop})_{\alpha}; \Delta E(ei)_{\alpha}; \Delta(BAE)_{\alpha}^{\bullet +}] \qquad (3)$$

where Δ denotes the relative magnitudes and the square parentheses imply summation of the three terms. It follows that $PA(\mathbf{6})_N - PA(\mathbf{5})_N = [18.6;\ 11.7;\ -3.7] = 26.6$ kcal mol^{-1} meaning that the amplified basicity of **6** in the gas phase originates from the ease of ionization and better accommodation of the positive charge reflected in the relaxation energy of 11.7 kcal mol^{-1}, which is somewhat diminished by a slightly lower bond association energy. Examination of bond lengths in **6H**$^+$ shows that all guanidino groups participate in the cationic resonance effect, which is larger than that in **5H**$^+$ due to a larger number of NMe_2 substituents. This pattern is even more pronounced in **7**, where $PA(\mathbf{7})_N - PA(\mathbf{5})_N = [25.6;\ 14.2;\ -4.2] = 35.6$ kcal mol^{-1}, meaning that the general picture remains the same. It should be noted that **7** is very close to the most powerful neutral base, *t*Bu-P4 synthesized so far,[7] the difference being the *t*Bu group at the imino nitrogen atom, which according to our calculations increases the PA value by only 1.1 kcal mol^{-1}.[10] It follows as a corollary that **6** and **7** should provide important rungs on the superbasicity ladder in the gas phase, whereas **4** should exhibit extreme basicity.

Let us now consider basicity in MeCN. It was shown that there is a very good correlation between the experimental pK_a (MeCN) and PAs calculated in MeCN:[10]

$$pK_a(\text{MeCN}) = 0.58684\,PA(\text{MeCN}) - 145.9 \quad (\text{in } pK_a \text{ units}) \qquad (4)$$

with the regression coefficient $R^2 = 0.997$ and the average absolute error of 0.3 pK_a units. The calculations are based on the polarized continuum model[24] and the isodensity molecular surface[25] of the solute molecule possessing a charge of 0.0004 e/B^3. Computations were performed at the B3LYP/6-311+G**//B3LYP/6-31G* level. The resulting pK_a values for **5**, **6** and **7** are 28.5, 37.8 and 42.2, respectively (Table 1). It appears that **6** is also a strong superbase in MeCN. It is 19 orders of magnitude more powerful than **1**. The strongest superbase, however, is **4** with a pK_a value of 44.8 units (Table 1) being 26 orders of magnitude more powerful than **1**.

To conclude, calculations suggest that replacement of the NMe_2 groups in **3** and **5** with guanidino moieties giving **4** and **6**, respectively, should provide very strong superbases both in the gas phase and MeCN.

It should be noted that the synthesis of three superbases related to **6** is just published.[26] They differ only in the substituents attached to the imino nitrogen N* involving H atom of Et and *t*-Bu groups. It is hoped that the superbase **4** will also be prepared soon.

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