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Extending the acidity ladder of neutral organic superacids—a DFT-B3LYP study of deprotonation of nonacyanofluorene

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Abstract—It was shown by a carefully selected B3LYP/6-311+G(2d,p)//B3LYP/6-31G(d) model that nonacyanofluorene and its most stable prototropic tautomer represent very powerful neutral organic acids both in the gas phase and in DMSO.

The notion of acidity is one of the pillars of chemistry. In the Brønsted definition acidity is the ability of a substance to lose a proton and of the resulting anion to accommodate the negative charge efficiently. It is common knowledge that acidity has immensely influenced the development of physical organic chemistry and contributed to the understanding of (electronic) structure/reactivity relationships.[1] Strong acids are valuable reagents in organic syntheses[2] and in industrial catalysis.[3] In particular, superacids are crucial in general acid catalysis, where the reaction rate is proportional to the concentration of the superacidic catalysts.[2] It is also well known that neutral organic acids have some preferable features, since anions obtained under mild reaction conditions participate in a large number of useful chemical transformations. Consequently, it comes as no surprise that much research interest has been devoted lately to the design of potent organic superacids.[4–10] In particular, it was shown that pentacyanocyclopentadiene[9] and heptacyanoindene[10] were extremely strong neutral acids both in the gas phase and in DMSO. It is the aim of this report to show that multisubstituted cyanofluorene is also a powerful organic superacid. For this purpose we used the density functional B3LYP/6-311+G(2d,p)//B3LYP/6-31G(d) model[11] (denoted hereafter as B3LYP), which represents a good compromise between reliability and practicality. The flexible triple zeta 6-311+G(2d,p) basis set used in the final single point calculations should be close to the asymptotic values of the total molecular energies estimated by the density functional theory.[12] Acidity is calculated as the enthalpy change ΔH_{acid} for the gas (g) phase reaction:

$$\mathrm{AH(g)} \rightarrow \mathrm{A^-(g)} + \mathrm{H^+(g)} \tag{1}$$

It has two contributions:

$$\Delta H_{\text{acid}} = \Delta E_{\text{acid}} + \Delta(pV) \tag{2}$$

where ΔE_{acid} is the change in the total molecular energy of the acid AH and its conjugate base $\mathrm{A^-}$, including both the zero-point vibrational energy (ZPVE) and the finite temperature (298.15 K) correction. The term $\Delta(pV)$ denotes the pressure–volume work term. The ZPVE and the temperature corrections were computed at the B3LYP/6-31G(d) level. All computations were carried out using the GAUSSIAN 98 program package.[13]

The B3LYP results (Fig. 1) show that the parent fluorene tautomer **1(a)** is by far the most stable, since it contains two aromatic fragments. Their aromatic character is reflected in the nucleus-independent chemical shift[14] [NICS(1)] calculated 1 Å above the ring critical point. The NICS(1) values are estimated by the gauge invariant atomic orbital approach[15] at the GIAO/HF/6-31G(d)//B3LYP/6-31G(d) level, whereas the ring critical points were identified by the atoms in the molecules theory of Bader.[16] The NICS[**1(a)**]$_5$ and NICS[**1(a)**]$_6$ values are −2.9 and −12.1 ppm, respectively, where indices 5 and

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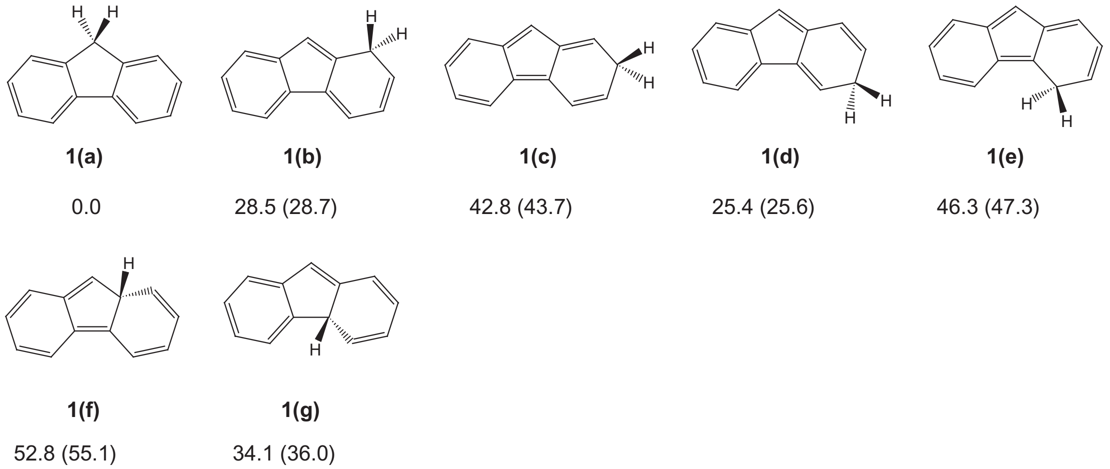


Figure 1. Schematic representation of fluorene tautomers together with their relative energies obtained by the B3LYP/6-311+G(2d,p)//B3LYP/6-31G(d) and B3LYP/6-31G(d) models. The latter values are placed within parentheses.

6 denote the five- and six-membered rings. It appears that the fused benzene rings assume NICS(1) values very close to that of benzene itself (−12.6 ppm). In contrast, the cyclopentadiene fragment is non-aromatic. A change introduced by deprotonation is interesting: the planar five-membered ring becomes more aromatic than its benzene counterparts as evidenced by NICS[**1(a)**$^-$]$_5$ = −15.5 ppm and NICS[**1(a)**$^-$]$_6$ = −12.7 ppm. The calculated B3LYP acidity of 351.4 kcal mol^{-1} (Table 1) indicates that fluorene is moderately acidic. A large amount of its acidity can be ascribed beyond any doubt to aromatization of the five-membered ring. We note in passing that the relative stability of tautomers is well reproduced at the simple B3LYP/6-31G(d) level (Fig. 1).

The acidity of fluorene is immensely amplified by multiple CN substitution. We consider here the nonacyano derivative of fluorene and its prototropic tautomers (Fig. 2). Tautomers involving two aromatic fragments are again the most stable ones. It is interesting to point out that a hydrogen walk to the CN group attached at the same C(sp^3) center leads to formation of the =NH imino functionality. This process embodies rehybridization of the atoms belonging to the C(sp^3)–C≡N fragment and the formation of a C(sp^2)=C=NH moiety resulting in an extended π-system containing an additional C=C double bond. It appears that the prototropic tautomer **2(b)** is more stable than **2(a)** by 2.9 kcal mol^{-1}. Since all the other tautomers are substantially less stable than **2(a)** and **2(b)**, we omit them from the following discussion. The deprotonation energies of **2(a)** and **2(b)** obtained by the B3LYP method are 259.8 and 263.1 kcal mol^{-1}, respectively (Table 1). It is interesting to compare these results with the DPEs in pentacyanocyclopentadiene[9] and heptacyanoindene,[10] which assume 263.5 and 262.5 kcal mol^{-1}, respectively. Consequently, it is safe to conclude that all three systems should be highly acidic and of similar strength. It is instructive to examine the NICS(1) values in **2(a)**, **2(b)**, and their common conjugate base. The NICS[**2(a)**]$_5$ and NICS[**2(a)**]$_6$ are −3.9 and −12.7 ppm, respectively. The corresponding values in **2(b)** are −7.7 and −13.0 ppm. It follows that CN substituents slightly increase the aromatic stability of fluorene. A dramatic increase in the aromaticity is observed upon deprotonation in analogy with the parent fluorene as evidenced by NICS[**2(a)**$^-$]$_5$ = −13.7 ppm and NICS[**2(a)**$^-$]$_6$ = −13.5 ppm, a notable difference being the uniformity of the aromatic character of five- and six-membered rings. Comparison of the NICS(1) values between **1(a)**$^-$ and **2(a)**$^-$ anions shows conclusively that the huge increase in acidity by multiple cyanation is a

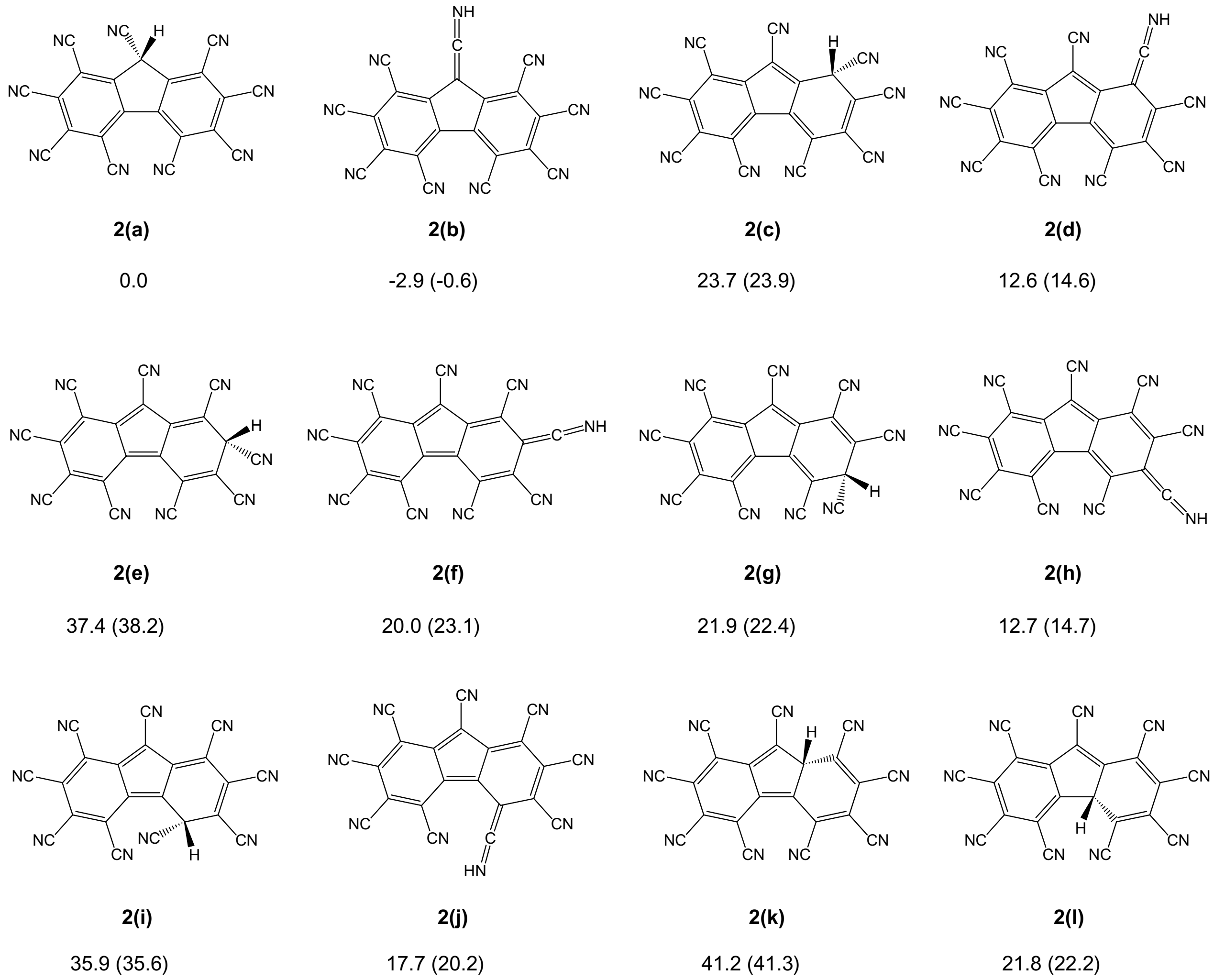
Table 1. Total molecular energies of the studied molecules in the gas phase (GP) and in dimethylsulfoxide obtained at the B3LYP/6-311+G(2d,p)//B3LYP/6-31G(d) level of theory

Molecule	E_{GP}[a]	E_{solv}[a]	H_{corr}[a]	ΔH_{acid}[b]	$\Delta_r H_{DMSO}$[b]	pK_a (theor)
1(a)	−501.55829	−501.56556	0.19832	351.4	46.6	23.1
1(a)$^-$	−500.98549	−501.06800	0.18320			
2(a)	−1331.85870	−1331.90235	0.19905	259.8	−18.2	−19.8
2(a)$^-$	−1331.43477	−1331.51092	0.18676			
2(b)	−1331.86326	−1331.92573	0.19828	263.1	−3.1	−9.7
2(b)$^-$	−1331.43477	−1331.51092	0.18676			
DMSO		−516.18147	0.08864			
DMSOH$^+$		−516.59926	0.09822			

H_{corr} denotes thermal correction to enthalpy obtained by the B3LYP/6-31G(d) model. Theoretical pK_a values are obtained using Eq. 4.

[a] In atomic units.

[b] In kcal mol^{-1}.



2(a) 0.0

2(b) -2.9 (-0.6)

2(c) 23.7 (23.9)

2(d) 12.6 (14.6)

2(e) 37.4 (38.2)

2(f) 20.0 (23.1)

2(g) 21.9 (22.4)

2(h) 12.7 (14.7)

2(i) 35.9 (35.6)

2(j) 17.7 (20.2)

2(k) 41.2 (41.3)

2(l) 21.8 (22.2)

Figure 2. Schematic representation of nonacyanofluorene tautomers together with their relative energies obtained by the B3LYP/6-311+G(2d,p)//B3LYP/6-31G(d) and B3LYP/6-31G(d) models. The latter values are given within parentheses.

consequence of the anionic resonance, which distributes the negative charge over the nitrogen atoms. Examination of the π-bond orders and nitrogen atomic charges corroborates this conjecture. It is impossible to obtain a reliable estimate of the barrier height for the hydrogen migration leading to tautomers **2(a)** and **2(b)** in view of the size of the systems. It is plausible to assume, however, that the barrier is high enough to enable the existence of both compounds. To put it in another way, it is safe to conclude that at least one of the prototropic tautomers **2(a)** and **2(b)** yields a highly potent organic superacid, which enters the region between the customary scales of basicity and acidity. A study of interactions between superacids **2(a)** or **2(b)** and some superbases belonging to the same range[17,18] will undoubtedly lead to interesting new features like spontaneous proton transfer and formation of compact ion pairs.

An inert solvent suitable for superacids is DMSO. Hence, we 'immersed' tautomers **2(a)** an **2(b)** in DMSO in silico and examine their behavior by employing a simple isodensity polarized continuum model (IPCM).[19,20] Our approach is based on the proton transfer reaction (3) between solute and the DMSO, which takes place in solution:

$$\mathrm{AH} + \mathrm{DMSO} \rightarrow \mathrm{A}^- + \mathrm{DMSOH}^+ + \Delta_r H_{\mathrm{DMSO}} \quad (3)$$

The enthalpies of proton transfer $\Delta_r H_{\mathrm{DMSO}}$ are very well correlated with the experimental pK_a values for a wide variety of neutral organic acids[21] yielding:

$$\mathrm{p}K_a\ (\mathrm{theor}) = 0.661 \times \Delta_r H_{\mathrm{DMSO}} - 7.7 \quad (4)$$

The pK_a values of **1(a)**, **2(a)**, and **2(b)** are 23.1, −9.7, and −19.8, respectively (Table 1). It follows that **2(a)** and **2(b)** are also very strong neutral acids in DMSO. We note in passing that the pK_a value of the most stable heptacyanoindene tautomer is −16.5 in the same solvent.[10]

Since the chemistry of fluorene[22–26] and the CN group is known,[27] we believe that the synthesis of nonacyanofluorene is possible and that this remarkable compound will be prepared in the future. This would contribute to bridging the gap between the ladders of (super)acids and (super)bases.

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