Theoretical Study of Strong Basicity in Aromatic Diamines

Eiichi Fujiwara, Kiyoyuki Omoto, and Hiroshi Fujimoto*

Division of Molecular Engineering, Kyoto University, Kyoto 606-01, Japan

The basic strength of NH_3, $NH_2(CH_3)$, $NH(CH_3)_2$, and $N(CH_3)_3$ has been evaluated by generating for each species the orbital that plays the dominant role in electron delocalization to an attached proton. The theoretically determined strength has been found to correlate well with the calculated value of proton affinity. The analysis has then been extended to a so-called "proton-sponge" compound, 1,8-bis(dimethylamino)naphthalene. The major component of the orbital of the diamine that captures the proton has been demonstrated to be an in-phase combination of two lone-pair orbitals. The out-of-phase combination elevated in energy by a strong antibonding interaction between two lone pairs of electrons is not necessarily the source of the exceptionally high basicity. The electrostatic interaction has been shown to be the major origin of stabilizing the protonated system, but the location of the captured proton is governed by electron delocalization. A similar conclusion has also been derived for 4,5-bis(dimethylamino)fluorene.

Introduction

Certain aromatic diamines have been reported to have exceptionally high basicity constants.[1,2] Alder and Hibbert have shown that 1,8-bis(dimethylamino)naphthalene (**1**) has a basicity 10 million times higher than that of *N,N*-dimethylaniline, while aniline and 1,8-diaminonaphthalene have basicities typical of aromatic amines.[3,4] Compounds having high basicity constants with other aromatic frames such as fluorene,[5−7] phenanthrene,[8] and others[9−13] have also been synthesized and examined.[3] Two effects have been suggested so far to be important in providing these compounds with such high basicity constants, one being the steric strain and destabilization that arise from the overlap of the nitrogen lone pairs and the other being the strong N···H···N hydrogen bonds which are formed upon monoprotonation.[2]

A through-space interaction between the two lone-pair orbitals in **1** has been shown to elevate their antibonding combination, n^-, about 2.0 eV above the bonding combination, n^+.[14] The $n^+−n^-$ separation is even greater in 4,5-bis(dimethylamino)fluorene, **2**, which shows a stronger basicity than **1**.[6] Thus, the high basicity of these molecules seems to be related to the strong repulsive interaction between two lone pairs of electrons.[2] On the other hand, Platts and Howard performed *ab initio* MO calculations on **2** and 4,5-bis(dimethylamino)phenanthrene, as well as **1**.[15,16] They showed that there was no apparent relationship between basicity and the N···N distance in the unprotonated base and in the protonated base in contrast to the arguments of Saupe et al.[8] Then, they suggested that the strength of hydrogen bond should play a large part in determining proton sponge basicity. Such an extraordinary strong basicity achieved by bringing two lone-pair orbitals in proximity will be of importance in understanding various phenomena, not only in chemistry but also in biochemistry. Here, we report the results of our analysis of the interaction between a proton and nitrogen lone pairs of electrons.

Results and Discussion

Proton Affinity of Simple Amines. In studying the basicities of proton sponge compounds, we introduce here a method of estimating the electron-donating potential of nitrogen lone pairs of electrons in terms of hybridized MOs and test the method for simple amines, NH_3, NH_2CH_3, $NH(CH_3)_2$, and $N(CH_3)_3$. The proton affinity of these amines was calculated very accurately by applying the *ab initio* MO method, including the electron correlation effects.[17] In the present study, the orbital analysis has been made with the 6-31G* basis set to see what orbitals of amines participate in bonding with a proton. The results of orbital analysis have been compared with the proton affinity estimated at the MP2/6-31G** level of theory. The calculations were carried out by applying the Gaussian 94 program.[18]

In the case of NH_3, the highest occupied (HO) MO having a strong p character plays the dominant role in electron delocalization to the attached proton. Other

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occupied MOs having the a_1 symmetry are located much lower in energy relative to the HOMO, and therefore, they do not participate significantly in electron delocalization. In methyl-substituted amines, the HOMO is delocalized over the carbons and hydrogens of the methyl groups. It is supposed, however, that the interaction is localized between the nitrogen atom and the attached proton in these amines. It will be necessary, therefore, to take other occupied MOs into account to compare the basicity of NH_3 and methyl-substituted amines.

To find out the orbitals of amines that are responsible for electron delocalization to the proton, we utilize here the scheme reported previously.[19-21] The distribution of electrons in a protonated ammonia molecule is located somewhere between the two configurations specified by $[NH_3 + H^+]$ and $[NH_3^+ + H]$. The electronic structure may be described approximately by a combination of the electron configuration representing $[NH_3 + H^+]$ and those representing single-electron excitations in which an electron is shifted from one of the occupied MOs of NH_3 to one of the empty orbitals of H^+, as in the treatment of charge-transfer complexes by Mulliken.[22] There are five occupied MOs in NH_3, and therefore 5×2 configurations for single-electron excitation at the 6-31G* level of theory. The coefficients of these electron configurations are obtained by carrying out a configuration analysis of the wave function for the stable structure of the protonated species of NH_3.[23]

Then, a paired transformation of the MOs in each of the two fragment species gives rise to a simpler expression of electron delocalization in terms of two configurations with single-electron excitation.[19-21] We obtain two hybridized MOs for each fragment in which an orbital of the NH_3 part makes a pair with an orbital of the proton to express the shift of an electronic charge from the former to the latter. Figure 1 illustrates the principal pair of orbitals representing the interaction between NH_3 and a proton and that representing the interaction between $N(CH_3)_3$ and a proton.[24] Here, the proton orbital is given by a combination of the inner and outer functions with the coefficients of 0.88 and 0.17, respectively, in the case of the proton attached to NH_3 and 0.75 and 0.33, respectively, in the case of the proton attached to $N(CH_3)_3$. The orbital of the amine part is seen to be localized well on the nitrogen atom both in NH_3 and in $N(CH_3)_3$, having the 2p AO extending in the direction to the attached proton as the major component.

The orbital ψ of an amine molecule obtained above is given by a combination of the occupied canonical MOs, ϕ_i ($i = 1, 2, ..., m$) where m is 5 in NH_3 and 17 in $N(CH_3)_3$, as denoted by eq 1. The coefficient d_i shows the magnitude and mode of contribution of the MO ϕ_i to the interaction, determined in the orbital transformation mentioned above.[19-21] The denominator has been attached to normalize the orbital. The electron-donating ability of the nitrogen in the amine is estimated then by
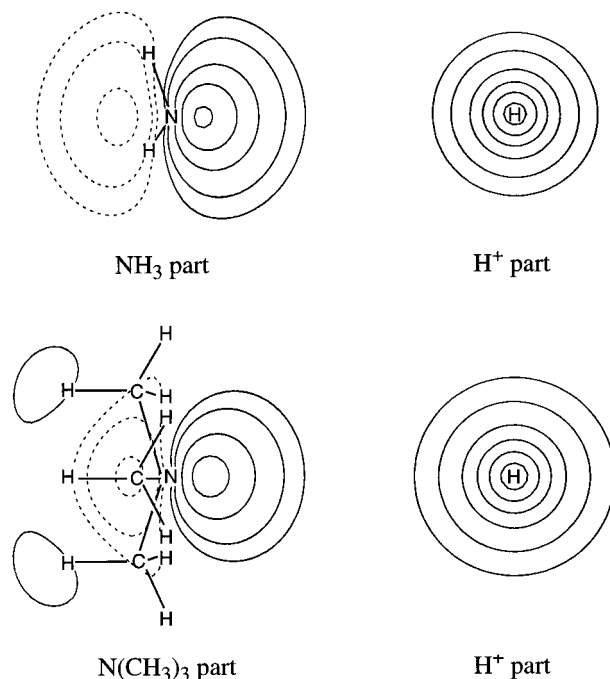
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(24) Another pair of orbitals consists mainly of diffuse atomic functions in each of the fragments, the proton and an amine, and gives a negligibly small overlap population.

Figure 1. Paired interaction orbitals for protonated ammonia and for protonated trimethylamine.

Table 1. Calculated Values of Proton Affinity and the Electron-Donating Ability of Nitrogen Atom in Several Amines

amine	proton affinity (kcal mol^{-1})	$-\gamma$ (au)	charge on H$^+$
NH_3	208.5^a (204.0^b)	0.419	0.512
$NH_2(CH_3)$	218.1^a (214.1^b)	0.391	0.528
$NH(CH_3)_2$	224.2^a (220.6^b)	0.373	0.539
$N(CH_3)_3$	228.0^a (225.1^b)	0.361	0.548
1	249.7^c (257.4^d)	0.382	0.472
2	253.0^c (260.6^d)	0.385	0.444

^{a} The proton affinity has been evaluated by $-PA = \Delta E_e + \Delta E_{therm.} +$ basis-set superposition error $- (5/2)RT$, where the first term indicates the energy difference between an amine and its protonated species at 0 K. $\Delta E_{therm.}$ includes the difference in electronic energy between 0 and 300 K, the difference in zero-point energy between the product and the reactants at 0 K, the change in the vibrational energy difference between 0 and 300 K, and the differences in vibrational energy and in translational energy between the product and the reactants (see ref 36). ^{b} Experimental values at 300 K (see ref 25). ^{c} Calculated at the RHF/6−31G* level of theory with 3−21G* zero-point energy correction scaled by a factor 0.89. ^{d} Difference in total energy between nonprotonated and protonated species calculated at the MP2//RHF/6−31G* level of theory.

taking the sum of the energies, ϵ_i, of the component MOs, weighted by the square of the coefficients, as defined by eq 2.

$$\psi = \left(\sum_{i=1}^{m} d_i \phi_i\right) / \left(\sum_{i=1}^{m} d_i^2\right)^{1/2} \quad (1)$$

$$\gamma = \left(\sum_{i=1}^{m} d_i^2 \epsilon_i\right) / \left(\sum_{i=1}^{m} d_i^2\right) \quad (2)$$

Table 1 gives the calculated values of proton affinity together with experimental values[25,26] and the electron-

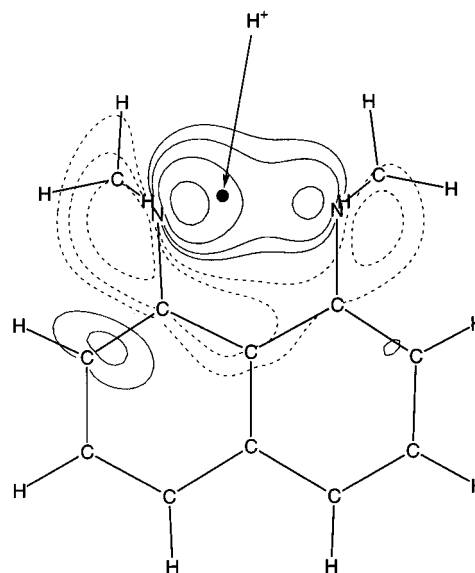(25) Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Chem. Phys. Ref. Data* **1984**, *13*, 695.
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donating potential of the nitrogen in amines. An excellent correlation is found to exist between the two calculated quantities. We have $\gamma = -0.42$ au for NH_3 and -0.36 au for $N(CH_3)_3$.[27] The methyl groups have elevated the level of the electron-donating orbital localized on the nitrogen atom in $N(CH_3)_3$ and, accordingly, have enhanced its strength as a base compared with NH_3. The amount of electronic charge shifted from an amine molecule to the proton calculated with the 6-31G* MOs by means of the Mulliken population analysis is shown to correlate well with the γ value.[28]

Proton Sponge Compounds. Now, we study the electron-donating ability of proton sponge compounds by using the method introduced above. As a typical species, we have carried out MO calculations on **1**. We have obtained the structure of **1** in an isolated state and of monoprotonated species of **1**, similar to those reported by Platts and Howard.[15] To avoid the repulsive interaction between the lone pairs of electrons on the two nitrogen centers, **1** is shown to be distorted from a C_s symmetric structure in an isolated state.[29-31] The two phenyl rings are slightly twisted. Protonation allows the molecule to form a nearly planar six-membered ring which consists of two nitrogens, a proton and three carbons of the naphthalene framework. The system has an asymmetrical proton bridge.[31-33] The barrier for proton transfer is low, being 3.8 kcal mol^{-1} at the RHF/6-31G* level with 3-21G* zero-point energy correction scaled by a factor 0.89 (-0.3 kcal mol^{-1} at the MP2//RHF/6-31G* level) and 5.2 kcal mol^{-1} in the literature.[15,34]
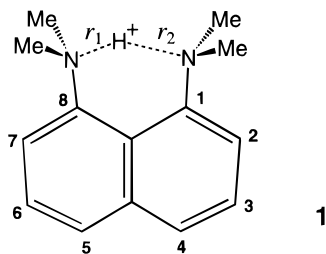
Platts and Howard have suggested that the proton sponge compounds have typical hydrogen-bond density properties, with a covalent N–H and an ionic N···H bond.[15] Figure 2 illustrates the interaction orbital of **1** obtained for the most stable structure of its monoprotonated species. The orbital of the proton part is much the

(27) By projecting the nitrogen components of the orbital ψ onto the unoccupied MO space of an amine molecule in an isolated state, we have obtained an orbital which is closest in the AO components to ψ. It is regarded as the origin of ψ (see: Fujimoto, H.; Satoh, S. *J. Phys. Chem.* **1994**, *98*, 1436). The electron-donating potential has been estimated to be 0.426, 0.400, 0.383, 0.376 au for NH_3, $NH_2(CH_3)$, $NH(CH_3)_2$, and $N(CH_3)_3$, respectively, in an isolated state. This indicates that the differences in the basic strength are traced back to these amines in an isolated state, as has already been noticed by Howard et al. See: Howard, S. T.; Foreman, J. P.; Edwards, P. G. *Can. J. Chem.* **1997**, *75*, 60.

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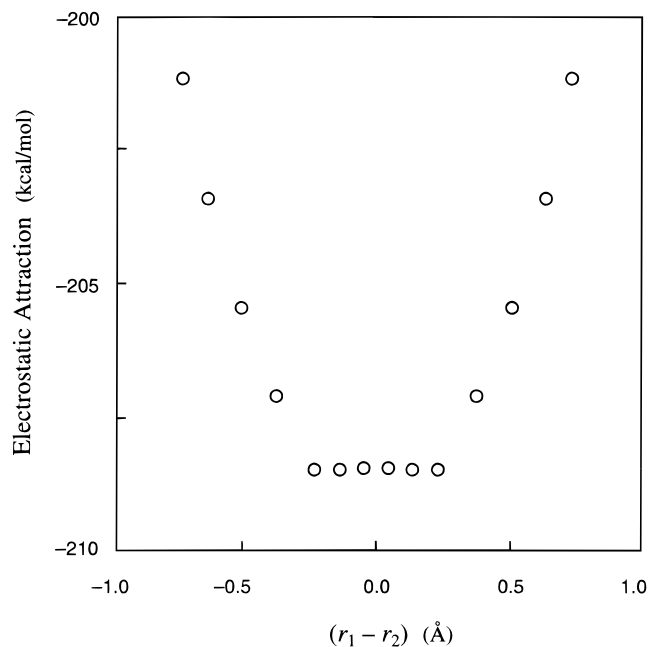
1, 8-bis(dimethylamino)naphthalene

Figure 2. Interaction orbital of 1,8-bis(dimethylamino)naphthalene. The location of the proton is marked by a dot. The paired orbital of the proton is essentially the same as that in the $N(CH_3)_3 \cdot H^+$ system and is not shown here.

same as that obtained for the $N(CH_3)_3 \cdot H^+$ system. It is shown that the proton is bonding with both of the two nitrogens, though there is a certain difference in bonding strength. Two lone pairs of electrons in proximity give rise to an *in-phase* combination n^+ and an *out-of-phase* combination n^-. We have imagined first that the n^- orbital elevated by a strong through-space antibonding interaction might be responsible for the strong basicity and the asymmetrical hydrogen bond in diamines such as **1**. We have found, however, that the contribution of the occupied MOs which have nodes between the two nitrogens of the approximately planar symmetric diamine fragment to the orbital that captures the proton is only 8.2% in weight. Electron delocalization takes place for the most part from the n^+ orbital. As a consequence, the potential barrier for the migration of the proton between two nitrogens should not be high in **1**, as demonstrated above.

In order to clarify the role of orbital interactions, we have made additional calculations. First, we have calculated the energy of the protonated species freezing the geometry of **1** to that in an isolated state. This has been shown to be less stable by 17.5 kcal mol^{-1} relative to the most stable asymmetrical hydrogen-bonded structure at the MP2//RHF/6-31G* level of theory. Though the strength of the hydrogen bond changes in the relaxation process, this may give a rough estimate of the relief of strain. Second, in order to see the contribution of the Coulombic attraction to the total energy, we have calculated the electrostatic potential of **1** for the structures which have been optimized for several $|r_1 - r_2|$ values to determine the barrier height for proton transfer mentioned above. The electrostatic potential is lower by 5.2 kcal mol^{-1} at the midpoint ($r_1 = r_2$) than at the most stable point, $|r_1 - r_2| = 0.70$ Å, as illustrated in Figure 3, at the MP2//RHF/6-31G* level. By comparing the energy of the monoprotonated system of **1** with an asymmetric hydrogen bridge obtained above with the energy of [**1** + a point charge] of the same geometry,

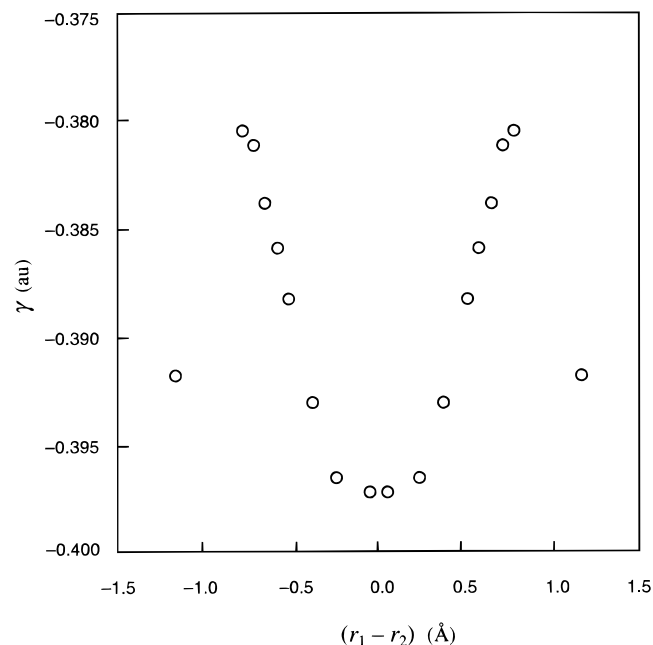**Figure 3.** Electrostatic interaction between a positive charge and 1,8-bis(dimethylamino)naphthalene.

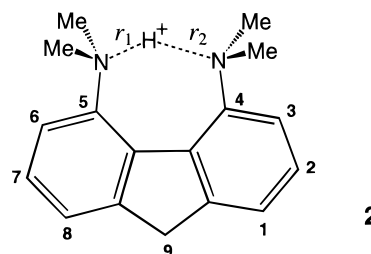**Figure 4.** Change in electron-donating potential of 1,8-bis(dimethylamino)naphthalene.

74.8% of the interaction energy is shown to come from the electrostatic attraction and the induced polarization in **1**. It is very interesting to see, however, that the asymmetrical proton bridge arises from the remaining part, i.e., orbital interactions.

To see if the electron-donating potential of **1** changes depending on the location of the proton, we have carried out an analysis for the monoprotonated species of **1**, similar to the one made above for small amines. We have evaluated the electron-donating ability of **1** from eq 2 by producing the interaction orbital. The result is presented in Figure 4. The ability is highest not at the center but in the vicinity where the protonation of **1** gives the largest stabilization. This indicates that the proton tends to sit on the position where an *in-phase* combination of the two

lone-pair orbitals is available and where the electron-donating ability of **1** has its highest value. The calculated value of proton affinity of **1** and the γ value are given in Table 1.

The electron-donating ability of **1** is not particularly large in magnitude compared with those of NH_3 and $N(CH_3)_3$. This is natural because the n^+ orbital which plays the dominant role in electron delocalization to the proton has been lowered in energy by a through-space bonding interaction, relative to the energy level of a separated lone-pair orbital. Now, it is clear that an exceptionally strong basicity of **1** should be ascribed not to electron delocalization but to a relief of strain as suggested[2] and to the formation of a strong cationic hydrogen bond. Note, however, that electron delocalization plays a crucial role in determining the location of the attached proton.

In order to examine the connection between the position of the attached proton and the electron-donating potential of amines, we have carried out a similar analysis on another proton-sponge compound, **2**. There was a controversy on the structure of the monoprotonated species of **2**. The species was suggested to have a symmetrical hydrogen bond,[3] while an NMR study supported an asymmetrical hydrogen bond.[35] The two phenyl rings are twisted from each other in an isolated state, the $C^4-C-C-C^5$ dihedral angle being 12.7°. The fluorene skeleton is relaxed to have a nearly planar structure in the protonated species.[16] Two energy minima each corresponding to an asymmetrical hydrogen bond have been shown to be separated by a small energy barrier, 3.7 kcal mol^{-1} in the present study at the RHF/6-31G* level of theory with 3-21G* zero-point energy correction scaled by a factor 0.89 (−0.6 kcal mol^{-1} at the MP2//RHF/6-31G* level) and 5.2 kcal mol^{-1} in the literature.[16,34]

The electron-donating potential of **2** has been evaluated by generating the interaction orbitals. As illustrated in Figure 5, the electron-donating potential estimated using eq 2 gives the highest value not at the center but at the position with $|r_1 - r_2| \cong 1.0$ Å. Electron delocalization is shown again to favor an asymmetrical hydrogen bond. The calculated proton affinity and γ value of **2** are presented in Table 1.

The two phenyl rings carrying the dimethylamino groups are twisted more significantly in an isolated state of 4,5-bis(dimethylamino)phenanthrene, compared with **2**. The angle is reduced, but they are still twisted in the protonated species.[16] Unlike the case of **1**, a seven-membered cycle is formed upon protonation, involving the attached proton, two nitrogens of dimethylamino groups, and four carbons of the phenanthrene framework

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(36) Foresman, J. B.; Frisch, M. J. *Exploring Chemistry with Electronic Structure Methods*; Gaussian, Inc.: Pittsburgh, PA, 1995; p 114. See also: Yamabe, S.; Hirao, K.; Wasada, H. *J. Phys. Chem.* **1992**, *96*, 10261.
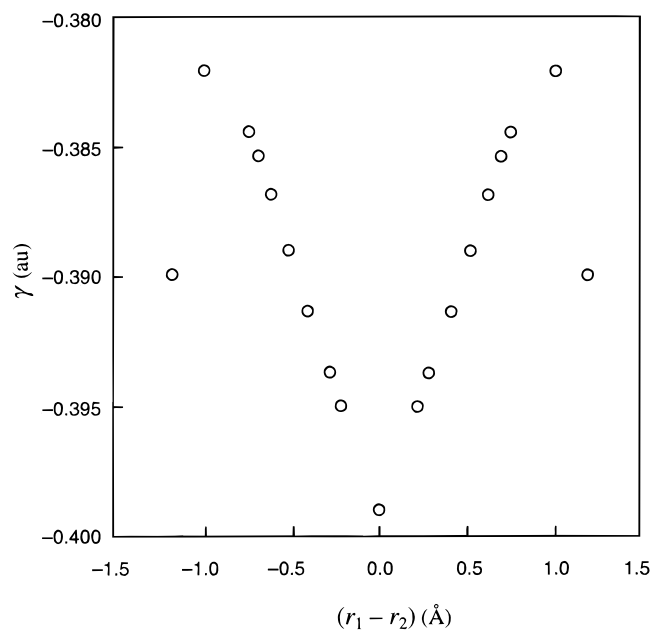
Figure 5. Change in electron-donating potential of 4,5-bis(dimethylamino)fluorene.

in 4,5-bis(dimethylamino)phenanthrene. The shorter N−N distance compared to that of **2** in an isolated structure forces the phenanthrene framework to remain still distorted from planarity in interaction with a proton. The removal of repulsion between two nitrogen lone pairs of electrons is clearly of importance, but recovery of the conjugation energy in the carbon skeleton should be another important source of stabilization in proton-sponge compounds, particularly in 4,5-bis(dimethylamino)phenanthrene. This might explain the observation that there was no apparent relationship between basicity and the N···N distance in the unprotonated base and in the protonated base.[15,16] Incidentally, our calculations on 1-(dimethylamino)-8-(methylamino)naphthalene have shown that an internal hydrogen bond stabilizes the species, giving a reason why 1,8-diaminonaphthalene has a basicity constant similar to that of aniline.[3,4]

Conclusion

The interactions between a proton and NH_3, $NH_2(CH_3)$, $NH(CH_3)_2$, and $N(CH_3)_3$ have been analyzed by generating for each species the orbital that plays the dominant role in electron delocalization. The proton affinity has been demonstrated to correlate well with the electron-donating ability of the nitrogen center in these amines. It has been clarified by a similar analysis on a typical "proton-sponge" compound, 1,8-bis(dimethylamino)naphthalene, that the orbital of the diamine molecule that captures a proton is principally an *in-phase* combination of two lone-pair orbitals. The *out-of-phase* combination of two lone-pair orbitals is elevated in energy by a strong antibonding interaction, but it is not involved significantly in the interaction with the proton. Thus, the electron-donating ability of 1,8-bis(dimethylamino)naphthalene is estimated to be lower compared with that of $N(CH_3)_3$, and therefore, the exceptionally strong basicity of this compound should come from the electrostatic interactions with the proton and a relief of strain upon protonation. In contrast, the location of the attached proton has been demonstrated to be governed by electron delocalization. An analysis of another proton-sponge compound, 4,5-bis(dimethylamino)fluorene, gave a similar result, suggesting again the significance of electron delocalization in providing an asymmetric hydrogen bridge.

Supporting Information Available: Information on the geometries and energies of the species examined in this study (10 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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