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N−H and α(C−H) Bond Dissociation Enthalpies of Aliphatic Amines

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Abstract: Bond dissociation enthalpies (BDEs) of a large series of aliphatic amines (21) were measured by means of photoacoustic calorimetry. Despite the different structures studied in the primary, secondary, and tertiary amine series, the α(C−H) BDEs were found to be very similar for unconstrained amines with values very close to 91 kcal/mol. αC- and N-alkylation or introduction of an hydroxy group only slightly affect the BDEs, a fact in perfect agreement with calculations performed at different CBS levels. This demonstrates the predominance of the two-orbital−three-electron interaction involving the N and $\alpha C^{\bullet}$ orbitals. On the other hand, the N−H BDE decreases when going from primary to secondary amines. This result is interpreted in term of a hyperconjugation in σC−C bonds, which leads to a stabilization of the aminyl radical. For cyclized amines, the BDEs depend on the relative geometry of the singly occupied $\alpha C^{\bullet}$ orbital with respect to that of the N atom, disfavoring the two-orbital−three-electron interaction. However, such structures can exhibit through-bond interaction. For a crowded structure such as triisopropylamine, for which the $\alpha C^{\bullet}$ orbital is not coplanar with the nitrogen one, the relaxation of a strain energy allows the BDE to be comparable to flexible structures.

Introduction

The determination of bond dissociation enthalpies (BDEs) of amines has been the subject of intensive experimental and theoretical studies. However, important debates have arisen from the large degree of uncertainty associated with reported values: an overview of the range of BDEs, even for the simplest amines, is reported in ref 1. For example, α(C−H) BDEs of 84 and 94 kcal/mol, respectively, have been determined for the compounds $Me_2NCH_2{-}H$ and $H_2NCH_2{-}H$;[2] these reported values can be compared to the results of a previous study,[3] which were respectively about 85−87 and 88−89 kcal/mol. Moreover, an important question remains about the effect of the C- and N-alkylation on the α(C−H) BDE, which has been noted to be surprisingly large in ref 2 and ref 4 but very weak in ref 5. Therefore, the results available in the literature do not strongly consolidate our knowledge about BDEs of aliphatic amines.

The aim of this paper is to determine accurately the BDEs of a large variety of amine structures, by using photoacoustic calorimetry (PAC). This technique has been shown to be very powerful for the determination of thermodynamic parameters[6−9] and therefore can be very helpful to get more insight in the change of the BDE with the molecular structure. This paper extends, in a systematic manner, previous PAC studies performed in the literature.[1,5,10−13] The results obtained will be presented together with an interpretation of the BDE changes associated with the structures. All these results are clearly supported by the predicted BDEs calculated by highly accurate ab initio methods.

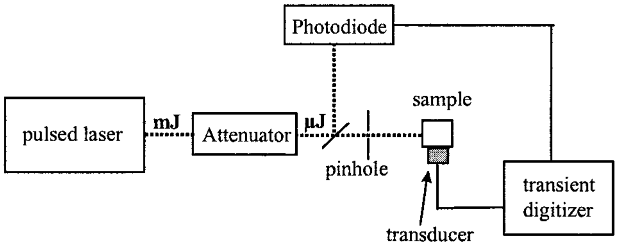

Figure 1. Typical experimental setup for photoacoustic calorimetry.

Experimental Section

The experimental setup for the PAC is shown in Figure 1. A nanosecond Nd:YAG laser (Powerlite 9010, Continuum) operating at 10 Hz with an energy decreased down to 7 mJ/pulse at 355 nm was

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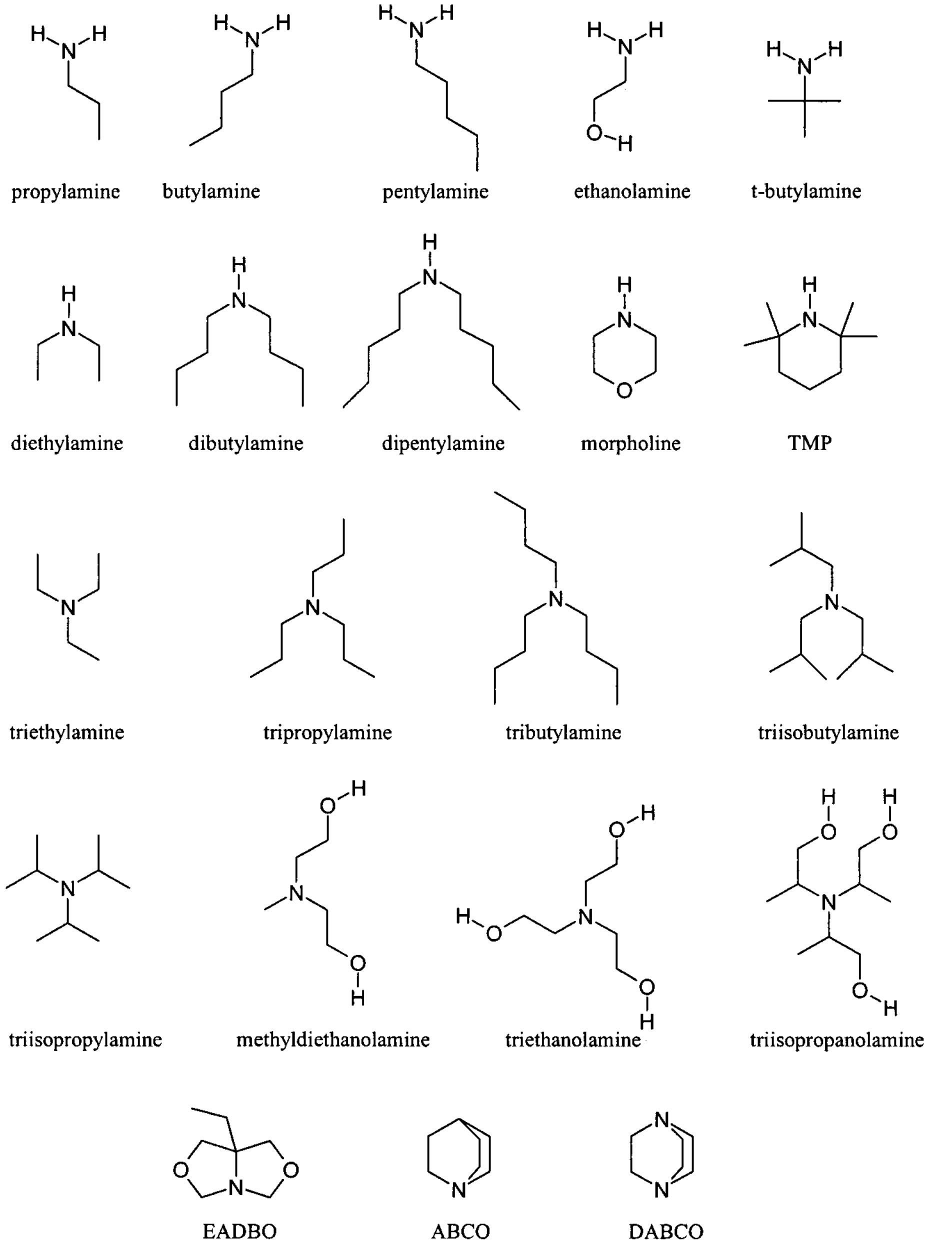
Chart 1



used as the excitation laser. A built-in seeder system improved the Gaussian shape of the laser beam. As a very low energy was required, a solution of 2-hydroxybenzophenone (BPOH) in acetonitrile was used as a chemical attenuator to obtain an incident pulse energy ranging from 0.5 to 100 μJ. The attenuated beam irradiated a 1-cm cell equipped with a piezoelectric detector (Panametrics A609S 5 MHz or A603S 1 MHz) through a 200- or 500-μm pinhole. The signals were amplified 10 times (Ortec 9301) and fed into a transient digitizer (Tektronix 3052). The optical density of the samples was adjusted to ~0.2 at the excitation wavelength. BPOH was used as standard. Oxygen was removed by bubbling argon for 15 min.

The time-resolved absorption spectroscopy (TRAS) setup is based on the Nd:Yag laser already described above. This system (LP900, Edinburgh Instruments) used a 450-W pulsed xenon arc lamp, a Czerny-Turner monochromator, a fast photomultiplier, and a transient digitizer (TDS 340, Tektronix). The instrumental response was 7 ns.

Solvents were spectroscopic grade and were used without further purification. The different amines studied are represented in Chart 1. All these compounds, including 2,2,6,6-tetramethylpiperidine (TMP), were distilled and stored under argon except 1-azabicyclo[2.2.2]octane (ABCO) and 1,4-diazabicyclo[2.2.2]octane (DABCO), which were sublimated. Triisopropylamine and 5-ethyl-1-aza-3,7-dioxabicyclo-[3.3.0]octane (EADBO) were used without further purification.

PAC Determination of BDE. (a) General Description of PAC. PAC is based on the detection of acoustic waves associated with the heat released in the medium after light absorption. This technique has been shown to provide important kinetic and thermodynamic information on the deactivation of transient species.[6,14] Indeed, photophysical deactivations occurring through nonradiative processes and exothermic photochemical reactions both release heat in the media. This conversion of light into heat causes a temperature jump associated to a variation of pressure ΔP, leading to the propagation of acoustic waves. The heat deposition can be considered as "fast" or "slow" depending on the following: (a) the time evolution of the chemical system, (b) the time width of the excitation pulse (typically 7−10 ns), (c) the time response of the detection equipment, and (d) the geometrical arrangement of

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the experimental setup.[15] Therefore, the experimental conditions have been adapted in order to consider that either the heat evolving from photophysical deactivation from upper excited states and from hydrogen abstraction reaction is detected as fast or the heat evolving from further radical recombination or secondary reactions is considered as slow, i.e., is not detected. The amplitude of the acoustic signal, which is proportional to ΔP and related to the fast heat released (S_{Fast}), can be described as

$$S_{\mathrm{Fast}} = K\alpha E_{h\nu}\,(1-10^{-A}) \qquad (1)$$

where K accounts for the thermoelastic parameters as well as for the experimental sensitivity, α is the fraction of the absorbed energy that is released as heat in the time window of the detection setup, $E_{h\nu}$ is the energy of the incident light, and the quantity $(1-10^{-A})$ is the fraction of light absorbed. A typical signal is shown in Figure 2a. The instrument was calibrated using BPOH, which is known to release the whole excitation energy in the solution in less than 1 ns and, therefore, can be used as a calorimetric reference.[6] Moreover, to avoid biphotonic processes, photothermal experiments are performed at very low pump intensity, and for every experiment performed, S_{Fast} is deduced by extrapolation at zero pump intensity (see, for example, Figure 2b).

(b) Application for the Determination of BDE. PAC experiments have already been used to determine BDEs of amines by measuring heat of reaction with *tert*-butoxyl radical (t-BuO$^\bullet$).[11,12] However, it is more convenient to use the triplet state of benzophenone (BP) for which the well-known reaction of a hydrogen abstraction from an amine (AH) leads to the aminoalkyl radical formation (A$^\bullet$):

$$^{3}\mathrm{BP} + \mathrm{AH} \rightarrow \mathrm{BPH}^{\bullet} + \mathrm{A}^{\bullet} \qquad (2)$$

The advantages of using benzophenone to determine the BDEs have been recently pointed out[1] and can be summarized as follows: (i) the reaction proceeds through an ultrafast electron transfer/proton transfer, and the heat of reaction corresponding to a net hydrogen transfer is deposited within the time response of the experimental setup, (ii) the quantum yields in ketyl radical can be easily quantified by TRAS allowing accurate measurements of BDEs, and (iii) no volume correction is needed in contrast to the method using the t-BuO$^\bullet$ radical.[9,11] The quenching of the BP triplet state by an amine leads to the formation of long-lived radicals for which are associated different enthalpies of formation compared to that of the reactants. If this reaction is carried out at a sufficiently high amine concentration, the heat associated with reaction 2 is released within the time window of the detection setup. The energy stored into the radicals is equal to $\phi_{\mathrm{rad}}E_{\mathrm{rad}}$, where ϕ_{rad} represents the quantum yield in produced radicals and E_{rad} the difference in the formation enthalpy between the radicals and the reactants. With respect to reaction 2, the BDE can be calculated according to

$$E_{\mathrm{rad}} = \Delta H_{\mathrm{f}}(\mathrm{BPH}^{\bullet}) - \Delta H_{\mathrm{f}}(\mathrm{BP}) + \mathrm{BDE(AH)} - \Delta H_{\mathrm{f}}(\mathrm{H}^{\bullet}) \qquad (3)$$

The experimental determination of ϕ_{rad} and S_{Fast} for a given system allows the determination of E_{rad} by the following energy balance:

$$E_{\mathrm{rad}} = (h\nu - S_{\mathrm{Fast}})/\phi_{\mathrm{rad}} \qquad (4)$$

The enthalpies of formation $\Delta H_{\mathrm{f}}(\mathrm{BPH}^{\bullet})$, $\Delta H_{\mathrm{f}}(\mathrm{BP})$, and $\Delta H_{\mathrm{f}}(\mathrm{H}^{\bullet})$ must be known in a given solvent. $\Delta H_{\mathrm{f}}(\mathrm{BPH}^{\bullet})$ is determined by PAC in acetonitrile and benzene by measuring the enthalpy of reaction of the benzophenone triplet state with benzhydrol according to a procedure described in the literature.[16] Similar values were obtained in both solvents with ΔH_f (BPH$^\bullet$) equal to 7.6 kcal/mol, in good agreement with that determined in ref 16. On the other hand, the same enthalpy of reaction for ^{3}BP with benzhydrol in acetonitrile and benzene indicates that $\Delta H_f\,(\mathrm{BP}) = -5.21$ kcal/mol[16] can be used in both solvents. Finally, ΔH_f (H$^\bullet$) was taken as 52.1 kcal/mol,[10,17] the enthalpy of solvation of the hydrogen atom in benzene and acetonitrile being the same.[9]

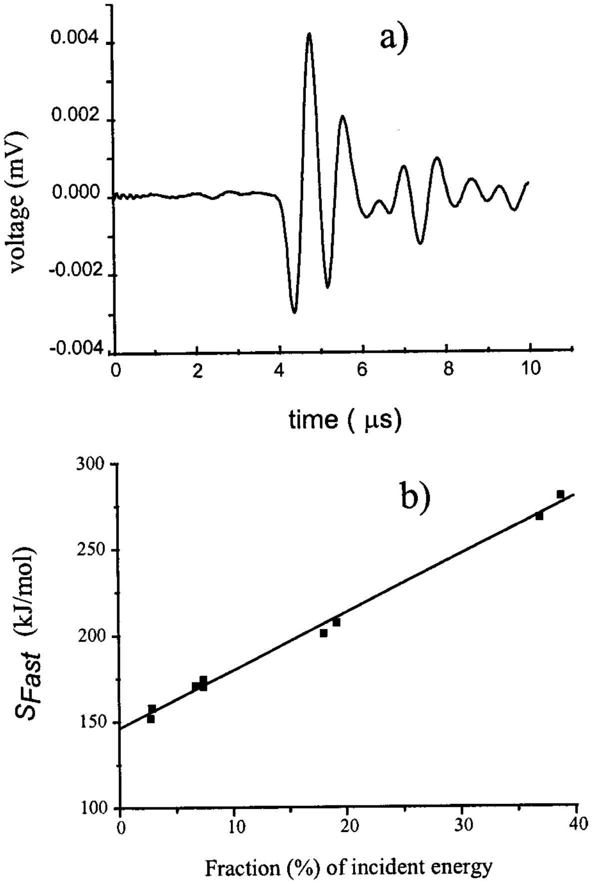

Figure 2. (a) Typical photoacoustic signal and (b) extrapolation of S_{Fast} at zero energy for the system ^{3}BP/propylamine in benzene.

Computational Methodology. Very efficient methods have been developed in the literature to predict accurately the thermochemical properties of the reaction. In a recent article, from the degree of uncertainty associated with BDE values previously reported, the authors concluded that one may plausibly argue that the best available values are probably those derived from recent high level ab initio calculations.[1] Beyond their high accuracy, one of the other advantages of these methods is the possibility to determine for a primary or secondary amine the α(C$-$H) and N$-$H BDEs independently. This potentiality is very interesting because this experimental differentiation is nearly impossible.

All quantum calculations were carried out using the Gaussian 98 suite of programs.[18] The CBS-4M and CBS-Q Complete Basis Set methods have been used. The most accurate C$-$H and N$-$H bond dissociation enthalpies were derived from heats of isodesmic reactions. With this method, the error in the calculated BDE is partially

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Table 1. Quenching Rate Constants k_q, Ketyl Radical Quantum Yields ϕ_{rad} and Experimental BDEs for the Amines Studied

		acetonitrile			benzene		
amine	bond	k_q (10^9 L mol^{-1} s^{-1})	ϕ_{rad}	BDE (kcal/mol)[a]	k_q (10^9 L mol^{-1} s^{-1})	ϕ_{rad}	BDE (kcal/mol)[a]
propylamine	[b]	0.25	0.91	93.1	0.25	0.87	91
butylamine	[b]	0.3	0.93	94			
pentylamine	[b]	0.3	0.91	95.5	0.3	0.87	90.5
ethanolamine	[b]	0.25	0.86	90.7			
tert-butylamine	N−H	0.09	0.92	93.3	0.06	0.8	95
diethylamine	[b]	4	0.92	88.6	4	0.71	87
dibutylamine	[b]	3.5	0.9	88.9	3.5	0.68	90.8
dipentylamine	[b]	3.5	0.92	91.9			
morpholine	[b]	3	0.92	92 (92.9,[c] 91−94[d])			
TMP	N−H				1.5	0.27	87.6[g]
triethylamine	α(C−H)	3	0.94	91.2	3.1	0.95[f]	91.2 (91.05[c])
tripropylamine	α(C−H)	3.5	0.92	89	3.2	0.95	90
tributylamine	α(C−H)	3.7	0.93	89.5			(91.05[c])
triisobutylamine	α(C−H)	3.1	0.92	92.8			
methyldiethanolamine	α(C−H)	2.5	0.92	87.1			
triethanolamine	α(C−H)	2	0.89	90.8			
triisopropanolamine	α(C−H)	1.6	0.94	93	1	0.95	90.8
triisopropylamine	α(C−H)				4.5	0.95	92.5
EADBO	α(C−H)	0.05	0.94	89	0.05	0.94	89.3
ABCO	α(C−H)				0.12	0.60	96.2
DABCO	α(C−H)				4.5	0.62	93.8 (93[e])

[a] Experimental error ∼2 kcal/mol, unless stated otherwise. [b] For primary and secondary amines, the BDEs gathered in this table represent in fact the BDEs of α(C−H) and N−H weighted by their importance in hydrogen abstraction process (see text). [c] Reference 5. [d] Reference 11. [e] Reference 21. [f] Value used as reference in benzene (see text). [g] Due to a lower ϕ_{rad} value, experimental error ∼4 kcal/mol.

counterbalanced by the error made in the calculation of the reference molecule. For the α(C−H) BDE, the isodesmic reaction was taken as

$$\mathrm{A{-}H + HOCH_2^{\bullet} \rightarrow A^{\bullet} + HOCH_2{-}H} \qquad (5)$$

and for N−H BDE

$$\mathrm{A{-}H + NH_2^{\bullet} \rightarrow A^{\bullet} + NH_2{-}H} \qquad (6)$$

The heat of reaction 5 or 6 is evaluated from ab initio calculations, and the BDE of the amine (A−H) can be deduced from

$$\mathrm{BDE\ (A{-}H) = BDE\ (R{-}H)} + \Delta H_{(5)\mathrm{or}(6)} \qquad (7)$$

R being $NH_2^{\bullet}$ and $CH_2^{\bullet}OH$ in the case of N−H and C−H bond cleavage, respectively. The well-established and recommended BDE values of 96 kcal/mol for α(C−H) BDE for methanol[5] and 107 kcal/mol for ammoniac[19] were used.

Results

The values of ϕ_{rad} were obtained through TRAS in acetonitrile by using the values of the extinction coefficients of the BP triplet state and the ketyl radical already found in the literature.[20] Only systems exhibiting ϕ_{rad} higher than 0.9 have been studied in this solvent in order to avoid any error arising from competitive reactions such as electron transfer. It is indeed the case with triisopropylamine or DABCO, for which the experiments have been performed in benzene in order to prevent free ion formation. In this solvent, ϕ_{rad} has been determined by comparison of the ketyl absorption for the studied amine with that obtained for ^{3}BP/triethylamine. For this reference system, very similar S_{Fast} values of 130 and 132 kJ/mol are obtained in benzene and acetonitrile, respectively. This fact, connected with the well-known α(C−H) BDE value for triethylamine[1,5] in nonpolar solvent (very close to 91 kcal/mol), corroborates the assumption of a similar BDE in both solvents, which allows the determination of a reference value of $\phi_{rad} = 0.95$ for this system in benzene.

The experimental BDE results obtained for amines represented in Chart 1 are gathered in Table 1 together with some recent values from the literature and measured with the same technique. A good agreement is found with the most recent BDE estimations available. For example, the morpholine BDE value was found equal to 92.0 kcal/mol, very close to the value of 91 kcal/mol recently reevaluated at 94 kcal/mol.[11] For triethylamine and tributylamine, a very good agreement is observed with differences lower than 2 kcal/mol,[1,5] which correspond to our experimental error. Moreover, the triethylamine value is confirmed by our previous study[10] carried out with an another photothermal technique (thermal lensing spectroscopy) by which a BDE of 91.5 kcal/mol has been determined. Another comparison can be made for DABCO: the α(C−H) BDE value of 93.8 kcal/mol is quite similar to that recently reported (93 kcal/mol[21]) from thermodynamic cycles.

All these comparisons with previous work give confidence to the method used, allowing a systematic study of the effect of the amine structure on the BDEs. Experimental BDEs determined in benzene are supposed to be very close to the gas-phase values[5,9] and therefore can be directly compared to the ones predicted. Moreover, it can be noted that the BDEs determined in both solvents are very close, within an experimental error of ∼2 kcal/mol. This indicates that the enthalpies of solvation of the aminoalkyl radical and the amine are similar in acetonitrile. For sake of comparison, ab initio calculations were performed to independently estimate the BDEs, and the results obtained are gathered in Table 2. For the α(C−H) BDEs, a very good agreement is found, as exemplified by the

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Table 2. Calculated BDEs of Amines at Different CBS Levels

amine	bond	CBS-4M	CBS-Q
methylamine	N−H	100.3	98.9 (99.1)[a]
	α(C−H)	92.3	92.6
ethylamine	N−H	100.8	99.4
	α(C−H)	91.1	91.5
propylamine	N−H	101	
	α(C−H)	91.3	
tert-butylamine	N−H	101	100.5
dimethylamine	N−H	95.4	93.9
	α(C−H)	91.7	92.1
diethylamine	N−H	95.5	93.9
	α(C−H)	90.8	91.3
TMP	N−H	95.9	
trimethylamine	α(C−H)	91.6	92.1
triethylamine	α(C−H)	91.7	
triethanolamine	α(C−H)	92.4	
EADBO	α(C−H)	92.4	
ABCO	α(C−H)	97.9	
DABCO	α(C−H)	97.1	
triisopropylamine	α(C−H)	91.7	

[a] BDE value determined at the G2 level (see text).

experimental BDE for triethylamine (91.2 kcal/mol), very close to the predicted value (91.7 kcal/mol) obtained at the CBS-4M level. However, for N−H BDEs, CBS-4M results are found ∼6−7 kcal/mol higher than the experimental values (see *tert*-butylamine and TMP). At the CBS-Q level, the predicted N−H BDEs decrease by ∼1−2 kcal/mol compared to the CBS-4M level. However, this slight decrease is not sufficient enough to account for the lower experimental BDEs measured by PAC. The difference is not clearly understood, but it can be reasonably supposed that the experimental N−H BDEs are slightly underestimated. This fact may originate from a more important experimental error induced by lower ϕ_{rad} values for *tert*-butylamine and TMP.

Discussion

A glance at the literature shows that the BDEs values of aliphatic amines are rather scarce and exhibit a large degree of variability, although some reliable experimental values appeared very recently for some compounds.[1,5] In addition, the fact that the hydrogen can be abstracted from both the N and C center for primary and secondary amines[22−29] rendered particularly tricky any discussion on the effect of substitution on both N−H and C−H BDEs. From the large number of molecules studied in this paper, some of these points can be examined in more detail.

Effect of N-Alkylation on the N−H BDEs. Very few values of N−H BDE were available from the literature. From the experimental values gathered in ref 2, it is generally accepted that the BDEs decrease with increasing the N-alkylation: BDE(H_2N−H) = 107 kcal/mol, BDE(CH_3HN−H) = 100 kcal/mol, and BDE($(CH_3)_2N$−H) = 92 kcal/mol. For these compounds, the decrease of the BDE is attributed to the ability of the methyl group to stabilize the radical by hyperconjugation resulting from the interaction of the unpaired electron with a localized σC−H molecular orbital.[30] This stabilization by hyperconjugation on the C−H bonds can be estimated by the difference in BDE between CH_3NH_2 and $(CH_3)_2NH$, ∼8 kcal/mol.

Two amines studied in this paper, *tert*-butylamine and TMP, do not exhibit any possibility for a α(C−H) dissociation and therefore can be used to probe this effect on more substituted compounds. A noticeable decrease of 7.4 kcal/mol of the experimental bond strength when going from primary to secondary amines can be observed in benzene (Table 1): the BDE of *tert*-butylamine, a typical primary amine, was found in benzene at 95 kcal/mol, while for the secondary amine TMP, BDE is 87.6 kcal/mol. This effect is first confirmed by CBS-4M calculations that predict a decrease of 5.1 kcal/mol of N−H BDE between *tert*-butylamine and TMP (Table 2). Since *tert*-butylamine and TMP do not contain any αC−H bonds, hyperconjugation can only result from stabilization with the MO based on the σC−C, in contrast with the series cited above (NH_3, CH_3NH_2, $(CH_3)_2NH$).

Therefore, these results clearly demonstrate that the N−H bond strength decreases from the primary to the secondary amines and that the stabilization by C−C hyperconjugation (7.4 kcal/mol) is close to that obtained by C−H conjugation (∼8 kcal/mol).

Effect of C-Alkylation on α(C−H) BDEs. The effect of C-alkylation on the α(C−H) BDE values can be disclosed by the investigation of trialkylamines. The following discussion will take advantage of the experimental BDE measurement of trimethylamine, measured by PAC and recently revised (91 kcal/mol).[11,13] Comparing this value with those obtained in this work for trialkylamines shows that α(C−H) BDE values are independent of the alkyl chain length. For example, trimethyl-, triethyl-, tripropyl-, tributyl-, and triisobutylamine have similar bond strengths. This is confirmed by CBS calculations, which show that α(C−H) BDEs of unconstrained trialkylamines are calculated to be ∼91.5 kcal/mol (Table 2). These results are clearly in contrast with previous studies[2] but agree very well with a recent work based on a few sets of compounds.[5] Moreover, at the G2(MP2) level, methylamine, ethylamine, and isopropylamine have been reported with the same BDE of 92.7, 91.7, and 92.7 kcal/mol, respectively. The lack of any effect of C-alkylation sharply contrasts with the behavior of alkanes exhibiting a significant decrease of C−H BDE in the primary, secondary, and tertiary series.[31] The presence of a N atom in the α position drastically modifies the properties of radicals involving conjugative electron delocalization between the N lone pair and the orbital of the unpaired electron.

When hydroxy groups are introduced on alkyl chains, a very slight effect of the oxygen atom at the β position can be found on the BDE. For example, comparison of triethyl-, triethanol-, and triisopropanolamine shows that the experimental BDEs are affected by less than 2 kcal/mol. This finding is clearly confirmed by the calculated BDEs (Table 2).

The very slight effect of the C-alkylation was clearly evidenced and leads to BDE values close to 91 kcal/mol for α(C−H) bonds of trialkylamines. The introduction of an hydroxy group leads to the same conclusion.

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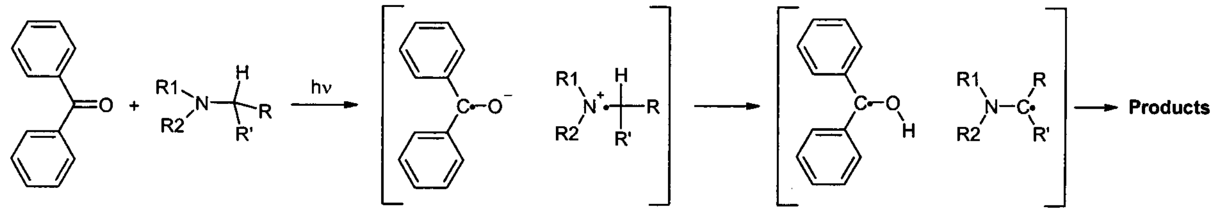
Scheme 1



N−H versus C−H Hydrogen Abstraction. Studies of hydrogen abstraction reactions from primary or secondary amines have often dealt with the nature of the atom (N or αC) where the hydrogen is abstracted.[22−26,29] For example, the reaction of *tert*-butoxyl radicals with dialkylamine can lead to both aminyl and aminoalkyl radicals[24] with a predominant abstraction from the carbon atom. For triplet ketones, the possibility of a N−H abstraction has been evidenced[22,23,25,26,29] with a conclusion similar to that for *t*-BuO$^•$ radicals. This remark can be tentatively illustrated by lower rate constants of interaction between the triplet state of benzophenone and TMP or *tert*-butylamine, which correspond respectively to about one-third and one-fifth of the quenching rate constants observed with secondary or primary amines possessing both the possibility of a N−H and α(C−H) hydrogen abstraction. However, it is well known that these rate constants of interaction represent the first step of hydrogen transfer corresponding to the electron-transfer reaction between benzophenone and amine (Scheme 1). In this case, the direct measurement of the fraction of hydrogen abstraction from N or C by the corresponding ratio of the quenching rate constant (as for *t*-BuO$^•$ [24]) does not seem valid. Therefore, on this basis, the value of the quenching rate constants does not allow one to discriminate the N−H and C−H abstraction even if the proportion of C−H abstraction is assumed to be the most important as shown in previous studies.

Being aware of this problem, it appears that the BDEs gathered in Table 1 represent in fact the α(C−H) and N−H BDEs weighted by their relative importance in the whole mechanism of hydrogen abstraction. Therefore, for primary and secondary amines holding an α(C−H) group, the BDEs are related to the real N−H and α(C−H) BDEs by the following relationship:

$$\mathrm{BDE}_{\mathrm{measured}} = \delta \times \mathrm{BDE}\alpha(\mathrm{C{-}H}) + (1 - \delta) \times \mathrm{BDE}(\mathrm{N{-}H}) \quad (8)$$

where δ represents the relative fraction of hydrogen abstraction from the αC center. Knowing the N−H BDEs (determined from *tert*-butylamine for primary amines and from TMP for secondary amines), the relationship between the experimental BDEs and the "intrinsic" α(C−H) BDEs of primary and secondary amines (exhibiting both N−H and α(C−H) abstraction abilities) can be discussed. The measured BDEs for primary and secondary amines (Table 1) are very similar to that of tertiary amines for which only α(C−H) abstraction occurs (the mean BDE value is ∼91 kcal/mol). At first sight, this fact can be explained as a dominant hydrogen abstraction process from the carbon atom. However, the N−H BDEs are close in energy to α(C−H) BDEs, as shown by the experimental values of *tert*-butylamine and TMP compared to those of other primary and secondary amines. Therefore, taking into account an experimental error of 2 kcal/mol, the determination of the relative fraction δ of hydrogen abstraction by PAC cannot be performed. Keeping in mind that the α(C−H) abstraction is assumed to be the most important process and assuming that the N−H BDE of TMP is representative of all those of secondary amines, one can conclude that the α(C−H) BDEs of secondary amines are close to the experimental ones, i.e., ∼91 kcal/mol. By applying a similar procedure for the primary amines, one can deduce that the α(C−H) BDEs for primary amines range between 91 and 94 kcal/mol in acetonitrile. In benzene, a value of 91 kcal/mol seems more appropriate, although no explanation can be given at the moment for the difference in BDEs observed in both solvents.

Primary, secondary, and tertiary amines exhibit α(C−H) BDEs close to N−H BDEs (∼91 kcal/mol). This renders impossible the determination of the relative fraction of N or C hydrogen abstraction by PAC. The consequence of such a property will now be discussed in detail.

Effect of N-Alkylation on the α(C−H) BDE of Amines. The consequence of N-alkylation on the α(C−H) BDE was the subject of debate and controversy for two decades.[1,2,4,5] This effect was noticed in former experimental studies.[2−4] However, this was not supported by a recent theoretical and PAC investigation.[5] Unfortunately, this latter work assumed that only C−H hydrogen abstraction by *t*-BuO$^•$ took place and therefore deserved some comments.[19] From the last section, it has been found that similar BDEs are obtained for primary, secondary, and tertiary amines with in all cases values near 91 kcal/mol, regardless of the alkyl chain length. The predicted BDEs gathered in Table 2 clearly confirm this trend, giving confidence to the experimentally determined values of α(C−H) BDEs. As a conclusion, N-alkylation does not significantly affect the BDE of aliphatic amines. This fact has been attributed to two antagonist effects on the two-orbital−three-electron interaction:[5] (i) the substitution by an alkyl group increases the possible stabilization, reducing the energy gap between the N lone pair orbital and the orbital (αC$^•$) of the unpaired electron, and (ii) on the other hand, this substitution has the effect of spreading the N lone pair thereby decreasing the magnitude of the interaction.

Energetics of the Two-Orbital−Three-Electron Interaction. The results obtained above cleared up the different effects involved in the stabilization of aminoalkyl radicals mainly occurring by conjugative electron delocalization between the semioccupied and the lone pair orbitals, allowing the sharing of electrons between the αC and N centers. From ESR exchange broadening experiments, this interaction has been evaluated at ∼7 kcal/mol for different unconstrained primary amines.[33] However, no information is available about the magnitude of this interaction for secondary or tertiary amines.

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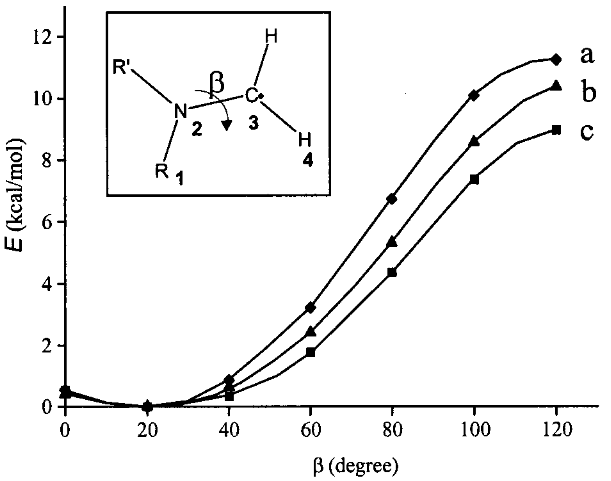

Figure 3. Potential energy surface for aminoalkyl radicals of (a) trimethylamine R = R′ = CH_3, (b) dimethylamine R = H, R′ = CH_3, and (c) methylamine R = R′ = H, associated with the dihedral angle β (inset).

This can be evaluated through the calculation of the potential energy surface associated with the C−N bond rotation at the B3LYP/6-31+G(d) level. Three radicals were calculated, from the starting methyl-, dimethyl- and trimethylamine molecules, by constraining the β angle (see Figure 3) at different values. Due to the slight pyramidalization of the N atom, the equilibrium structure of the radical is found for $\beta \sim 20°$. Increasing β leads to a more pyramidal structure of the nitrogen atom, resulting in a β value of $\sim$120° for the orthogonal N and α$C^{\bullet}$ orbitals. The results obtained are shown in Figure 3 and evidenced the importance of the two-orbital−three-electron interaction: a stabilization of $\sim$10 kcal/mol takes place when the N and α$C^{\bullet}$ orbitals are coplanar (the effect of the anticoplanar arrangement has been already discussed[5]). The stabilization reaches 9.0 kcal/mol for methylamine, a value in excellent agreement with the EPR results mentioned above for primary amines.

A slight effect of the N-alkylation is observed with the magnitude of the stabilization: 9 kcal/mol for methylamine, 10.3 kcal/mol for dimethylamine and 11.2 kcal/mol for trimethylamine. This fact clearly agrees with the very similar values of α(C−H) BDEs in the primary, secondary, and tertiary amine series, indicating the predominance of the two-orbital−three-electron interaction on the effect of N-alkylation.

Do Constrained Amines Exhibit a Particular Behavior? The calculation of the magnitude of the two-orbital−three-electron interaction underlines the importance of the coplanar arrangement of these orbitals. Cyclic compounds allow study of the effect of crowded structures for which the two orbitals involved are frozen in a given geometry. Such typical molecules are ABCO and DABCO. CBS-4M calculations show that the angle between the two orbitals are 77.8° and 77.1° in DABCO and ABCO radicals, respectively (Figure 4). Therefore, two-orbital−three-electron interaction can hardly take place,[32,34] and one should expect an increase in the BDE of $\sim$7 kcal/mol compared to unconstrained structures, on the basis of the calculation performed on trimethylamine (Figure 3). However, for DABCO, the experimental BDE value of 93.8 kcal/mol measured in benzene (Table 1), is only $\sim$3 kcal/mol higher than that of triethylamine and other tertiary unconstrained amines. The calculated value at the CBS-4M level of 97.1 kcal/mol is higher than that calculated for trimethylamine by 5.5 kcal/mol. The increase of the BDE reflects a destabilization of the radical that is related to the lack of a three-electron bond (although the magnitude of the destabilization is less than expected on the basis of the calculations performed on trimethylamine). Therefore, for the DABCO radical, another kind of stabilization is required in order to explain this relatively low BDE value. Delocalization of the SOMO over the whole molecule occurs with a through-bond σ(C−C) stabilization of the radical. It is particularly interesting to note that such a mechanism has always been evidenced [35−37] for the DABCO cation radical. Moreover, for a constrained molecule, the BDE is not a direct measurement of the relative radical stability.[5,13] Indeed, the separation between steric and electronic effects on the amine from those on the radical is not straightforward. For DABCO, in addition to a through-bond stabilization of the aminoalkyl radical, a strain energy change associated with the α(C−H) bond dissociation can also participate in the stabilization of the radical.

This situation is more pronounced in the case of ABCO, a structure very close to that of DABCO. Compared to DABCO, an increase of 0.8 kcal/mol in the BDE was predicted from CBS-4M calculations, and a BDE of 2.4 kcal/mol higher than that of DABCO was measured in benzene. This is in line with an expected decrease of the through-bond interaction, due to the lack of a second nitrogen that can participate in this stabilization of the radical, as for DABCO.

EADBO is a quite interesting compound that exhibits two five-membered rings including two oxygen atoms at the β position with respect to the nitrogen. A BDE of $\sim$89 kcal/mol can be determined both in acetonitrile and in benzene. This fact, associated with an efficient hydrogen abstraction in polar solvent, leads to the conclusion that a favorable stereoelectronic effect must occur: molecular modeling evidences a nearly coplanar arrangement of the hydrogen atom with the nitrogen lone pair in the parent molecule, as for flexible structures (Figure 4). It is interesting to note that the vicinity of the oxygen atom and the constraint imposed by the five-membered rings have only a slight effect on the BDE, as already noted for unconstrained hydroxyalkyl substituted amines.

The Case of Triisopropylamine. Due to the presence of bulky substituents, the equilibrium structure of triisopropylamine significantly differs from uncrowded amines: the three N−C bonds are nearly coplanar with a sum of C−N−C angles computed at 359.9°, in agreement with experimental and theoretical reports.[38−40] The α(C−H) angle was slightly tilted out of the NC_3 plane (Figure 4). In this case, a stabilization of the radical similar to that observed for flexible amines cannot occur without any twisting of the $CH_3C^{\bullet}CH_3$ group. Previous studies[34] demonstrated for this compound a high quantum yield of ionic species in a polar solvent. Therefore, it was concluded that either an unfavorable approach of ^{3}BP to the α(C−H) or a loss of stabilization prevents the hydrogen abstraction reaction. From our experiments, very similar results are observed in

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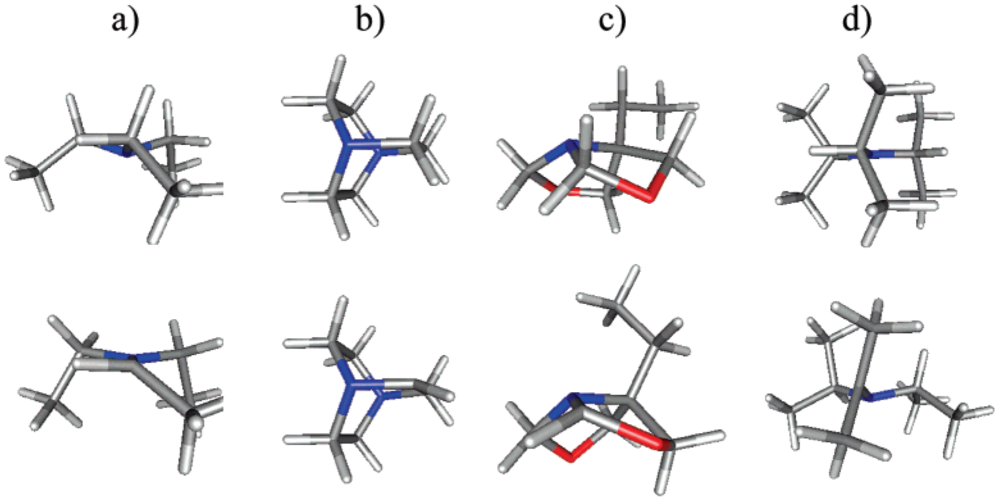


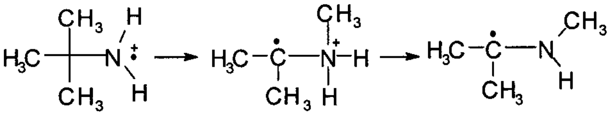
Figure 4. Representation of optimized structures of amines (upper structures) and aminoalkyl radicals (lower structures): (a) triethylamine, (b) DABCO, (c) EADBO, and (d) triisopropylamine.

acetonitrile, preventing the study of triisopropylamine in this solvent. However, in benzene, the ^{3}BP/triisopropylamine system leads to the observation of BPH$^\bullet$ (as in the case of DABCO), clearly indicating the occurrence of a hydrogen abstraction reaction. Moreover, the high quantum yield of ketyl radicals allows the α(C−H) BDE to be determined accurately. The value obtained (92.5 kcal/mol) is very close to those of unconstrained tertiary amines. The predicted BDE at the CBS-4M level (close to that of triethylamine) confirms this trend. This value is lower than expected from the increase of BDE resulting from a lack of stabilization.

Figure 4 shows that, as expected, two-orbital−three-electron bond stabilization cannot take place in the corresponding aminoalkyl radical due to an orthogonal conformation of the αC$^\bullet$ orbital with respect to the nitrogen lone pair orbital. The relatively low value of BDE should therefore be explained on the basis of a strain energy taking place in the amine that relaxes in the radical. Indeed, an important strain change is expected due to the equilibrium geometry essentially characterized by three coplanar N−C bonds leading to a nonpyramidal structure of the nitrogen atom that is different from the more pyramidal radical structure, as represented in Figure 4. Pyramidalization of the radical occurs due to the relaxation of the constrained amine structure, as indicated by the sum of C−N−C angles equal to 348.5°. Thus, hydrogen abstraction leads to a conformational reorganization of the isopropyl groups. Calculation of the energy of the radical in a constrained geometry close to that of the parent molecule (i.e., with a sum of C−N−C angles equal to 359.5°) leads to a BDE value of 94.8 kcal/mol. This means that the strain energy is ~3.1 kcal/mol for this structure. Such a behavior has been already invoked to explain the decrease of 2 kcal/mol of the BDE of pyrrolidine compared to triethylamine.[5,13] In this latter case, the important strain change associated with the C−H eclipsing interactions occurring in the parent molecule (which does not take place in the radical structure) explains this difference.

The lack of two-orbital−three-electron interaction in this orthogonal arrangement of the aminoalkyl radical renders this structure very close to that of typical alkyl radicals. In this case, the stabilization arises from the classical C$^\bullet$-alkylation:[31] the C−H BDEs of secondary alkanes are weaker by ~4 kcal/mol compared to primary ones, allowing a greater stabilization of the $CH_3C^\bullet CH_3$. These two effects, i.e., decrease of the strain energy and stabilization of a secondary carbon radical, explain the relative low BDE of triisopropylamine.

Scheme 2



Conclusion

In this paper, a systematic study of the BDEs of 21 representative amines by photoacoustic calorimetry and theoretical calculations has provided new results and insights that have yielded an improved understanding of structure/property relationships. For example, the following points have been clearly pointed out: the use of two original amines (*tert*-butylamine and TMP) suggests that the stabilization, observed in the effect of the N-alkylation on their N−H BDEs, occurs through C−C hyperconjugation; C-alkylation clearly has no effect on α(C−H) BDEs; N−H and α(C−H) BDEs are close in energy; the effect of the N-alkylation on the α(C−H) BDEs is ascribed to a two-orbital−three-electron interaction whose magnitude has been evaluated for primary, secondary, and tertiary amines; in constrained amines where this classical stabilization does not take place, the role of the through-bond stabilization (in ABCO and DABCO aminoalkyl radicals) is clearly evidenced; in triisopropylamine, which exhibits a crowded structure, the existing strain energy relaxes in the radical. All the experimental results, in good agreement with modeling calculations shed some light on the behavior of aliphatic amines toward hydrogen abstraction.

Appendix

One of the reviewers suggests that the difference between the calculated N−H BDEs and the determined ones (~6 kcal/mol for *tert*-butylamine and ~7 kcal/mol for TMP) could arise from the occurrence of a secondary chemical rearrangment that leads to an “extra” heat release and hence to an apparently lower BDE (Scheme 2).

One way to deal with this proposal is to carry out steady-state photolysis with product analysis. This kind of experiment was already reported in the literature,[22] the yield of photoreduction of benzophenone by *tert*-butylamine being reported to be 0.06. This low yield was interpreted as the result of a very efficient recombination of the aminyl radical with the ketyl radical, leading to the starting material. On the contrary, efficient photoreduction was observed in the case of an aminoalkyl radical (as triethylamine). Therefore, one can consider that (i) the low yield is typical of a N−H abstraction, and (ii) if the 0.06 side products arise from the reaction depicted in Scheme 2, this will lead to an error of only 0.5 kcal/mol in the apparent BDE. Therefore, at the moment, the literature does not provide strong evidence supporting this proposition, although it would be interesting to investigate this attractive hypothesis more deeply.

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