Intramolecular Hydrogen Bonding and Hydrogen Atom Abstraction in Gas-Phase Aliphatic Amine Radical Cations

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The intramolecular hydrogen atom abstraction by the nitrogen atom in isolated aliphatic amine radical cations is examined experimentally and with composite high-level ab initio methods of the G3 family. The magnitude of the enthalpy barriers toward H-atom transfer varies with the shape and size of the cyclic transition state and with the degree of substitution at the nitrogen and carbon atoms involved. The lower barriers are found for 1,5- and 1,6-abstraction, for chairlike transition states, for abstraction reactions in ionized primary amines, and for abstraction of H from tertiary carbon atoms. In most cases, the internal energy required for 1,4-, 1,5-, and 1,6-hydrogen atom abstraction to occur is less than that required for gas-phase fragmentation by simple cleavage of C−C bonds, which explains why H-atom transfer can be reversible and result in extensive H/D exchange prior to the fragmentation of many low-energy deuterium labeled ionized amines. The H-atom transfer to nitrogen is exothermic for primary amine radical cations and endothermic for tertiary amines. It gives rise to a variety of distonic radical cations, and these may undergo further isomerization. The heat of formation of the gauche conformers of the γ-, δ-, and ϵ-distonic isomers is up to 25 kJ mol^{-1} lower than that of the corresponding trans forms, which is taken to reflect C−H−N hydrogen bonding between the protonated amino group and the alkyl radical site.

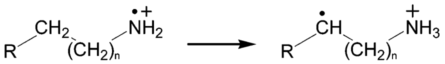
Introduction

Aliphatic amine radical cations isomerize by intramolecular hydrogen atom abstraction in the gas phase,[1−6] in solution,[7−10] and in low-temperature halocarbon matrixes.[11] In the gas phase, these reactions are reversible and often result in extensive intramolecular hydrogen atom exchange.[2−6] The exchange has been observed experimentally in deuterium labeled propylamine and longer amine radical cations and involves five-membered or larger cyclic transition states (up to eight-membered transition states have been suggested).[6] The C-to-N hydrogen atom transfers convert the amine radical cations to distonic isomers[12] (Scheme 1); these may subsequently undergo reactions that result in rearrangement of the carbon skeleton via cyclopropane intermediates[3,13] formed by ring closure of γ-distonic ions (Scheme 2) or in nitrogen atom migration via intermediate β-distonic ions[4,14−16] (Scheme 3).

In the condensed phase, intramolecular hydrogen atom abstraction in amine radical cations is a key step in the Hofmann−Löffler−Freytag reaction[7] and related processes.[8] 1,5-H-atom abstraction appears to be strongly preferred, but reactions involving larger transition states have been reported.[7−10,17] Electron paramagnetic resonance (EPR) studies of the abstraction reactions were described very recently.[11]

An early computational study by Yates and Radom[18] examined the intramolecular hydrogen abstraction in four straight-chain primary amine radical cations; more recently, Janovský et al.[11] used density functional theory (DFT) methods to study the reactions of ionized propyl- and butylamine. The present investigation employs composite ab initio methods that include electron correlation beyond the MP2 level to examine the H-atom transfer to nitrogen in the radical cations of primary, secondary, and tertiary amines with straight as well as branched alkyl chains in a variety of conformations. The aim is to examine how the enthalpy barriers toward hydrogen atom abstraction vary with the size of the transition states and with the degree of substitution at the nitrogen and carbon atoms involved, to establish the role and requirements of the intramolecular H-atom abstraction that precedes the skeletal rearrangement reactions of amine radical cations (Schemes 2 and 3).

SCHEME 1



Methods and Results

Computational Thermochemistry. Heats of formation of amine radical cations, of their distonic isomers, and of the transition states for intramolecular hydrogen atom transfer were derived from total energies calculated with the G3 and G3(MP2) composite ab initio methods,[19,20] slightly modified in that the geometry optimization was performed at the UMP2(full)/6-31+G(d,p) level. These methods have been shown to yield accurate estimates of the thermochemical properties of ions and radicals.[21−23] The energies were obtained with the Gaussian 98 suite of programs[24] and converted to 298 K heats of formation as described by Nicolaides et al.;[25] the required auxiliary thermochemical data were taken from the recent NIST-JANAF compilation by Chase.[26] Preliminary location of transition states for H-atom abstraction was performed by stepwise changes of the C−H (or N−H) bond lengths in the appropriate gauche conformer of the reactant ion. Additional calculations were carried out with composite methods that employ DFT calculations to determine the molecular geometry and the vibrational frequencies, the G3//B3LYP[27] and CBS-QB3 methods.[28]

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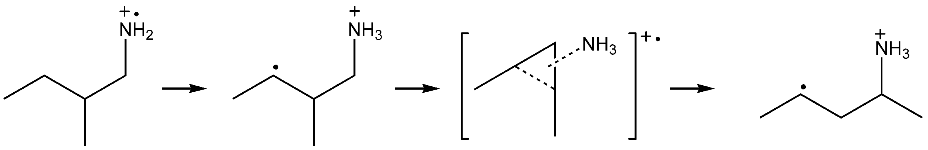
SCHEME 2



SCHEME 3

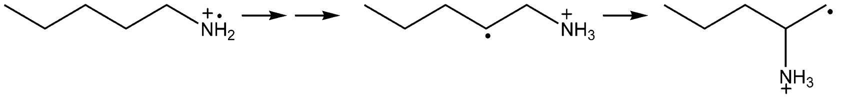


TABLE 1: Calculated Heats of Formation of the Species Involved in (the Hypothetical) Intramolecular 1,2- and 1,3-Hydrogen Atom Abstraction by the Amino Group in Primary, Secondary, and Tertiary Aliphatic Amine Radical Cations

R	molecular ion[a]	TS(1,2)[b]	α-distonic isomer[b]	TS(1,3)[b]	β-distonic isomer[b]	simple cleavage[c]
			$RNH_2^{+\bullet}$			
methyl	855	+154	−5			
ethyl	812	+134	−20	+127	−25	+83
isopropyl	765	+119	−29	+125	−24	+45
propyl	778	+141	−11	+109	−35	+95
butyl	751		−10	+108	−32	+102
pentyl	727		−9	+109	−30	+106
isobutyl	740		−6	+94	−40	+103
			$RNHCH_3^{+\bullet}$			
methyl	792	+180	+29			
ethyl	751	+162,[d] 181[e]	+14, 28[e]	+154	+10	+102
isopropyl	707	+153	+4	+150	+11	+69
propyl	721	+165	+19, 32[e]	+135	−3	+110
butyl	696			+132	−2	+115
isobutyl	687			+119	−11	+114
			$RN(CH_3)_2^{+\bullet}$			
methyl	737	+197	+54			
ethyl	699[f]	+185, 197[e]	+36, 52[e]	+170	+34	+115
isopropyl	659	*g*	+29	+168	+37	+93
propyl	670	+187	+40, 55[e]	+150	+20	+122
isobutyl	636			+137	+13	+126

[a] G3 heats of formation; kJ mol^{-1}, 298 K. [b] G3(MP2) heat of formation relative to the molecular ion; kJ mol^{-1}, 298 K. [c] Sum of the heats of formation of the products of cleavage of the α-C−C bond relative to the molecular ion. [d] Methyl groups trans; the cis TS is 5 kJ mol^{-1} higher in energy. [e] 1,2-H-abstraction from CH_3. [f] In the lower-energy conformation, both *N*-methyls are gauche to the *C*-methyl. [g] Transition state not located.

Tables 1−4 summarize the calculated heats of formation of simple aliphatic amine radical cations in the all-trans and various gauche conformations. These tables also include results for the transition states for H-atom transfer between C and N as well as the heats of formation of the α-, β-, γ-, δ-, and ε-distonic isomers that would arise by hydrogen atom transfer. The heats of formation of the all-trans conformer of the amine radical cations included in the tables are derived from G3 calculations. The results for isomeric species (gauche conformers, distonic isomers, and transition states) are given relative to the corresponding all-trans molecular ion; these energy differences are for reasons of computational economy determined with the G3(MP2) method. When applied to systems of the present kind, this method yields heats of formation that are as a rule some 4−7 kJ mol^{-1} higher than the G3 values; however, the G3(MP2) energy differences between isomeric species reproduce the G3 energy differences quite well. In addition, the heats of formation of several of the stable species and transition states examined in this study were also derived from energies obtained with the CBS-QB3 method and the G3//B3LYP and G3(MP2)//B3LYP methods, to examine possible differences arising from the alternative determination of the geometry and vibrational frequencies of the stationary points found. The results obtained (not included in the tables) were in most cases within 1−2 kJ mol^{-1} of those in Tables 1−4. Spin contamination was negligible in all cases examined; the calculated $\langle S^2 \rangle$ value was between 0.76 and 0.78.

In Tables 2 and 3, a number of heats of formation are given in parentheses. These results are associated with some uncertainty, owing to possibly inaccurate estimates of the zero-point vibrational energy (zpve) and heat capacity (C_p) contributions (discussed in more detail below).

Comparisons of the enthalpy barriers with the energy required to undergo simple cleavage of the α-C−C bond are based on the recently reported G3 and G3(MP2) heats of formation of the products of α-cleavage, alkyl radicals and immonium ions.[29]

Mass Spectrometry. The predominant fragmentation reactions of gas-phase amine radical cations occur by the cleavage of C−C bonds. These reactions can be observed directly, in mass spectrometers. Evidence for (reversible) H-atom abstraction is obtained from the same experiments, though indirectly, inasmuch as reversible abstraction in, for example, *N*-deuterated amines results in H/D exchange, which causes incorporation of deuterium atoms in the alkyl radicals subsequently expelled by fragmentation.

The fragmentation reactions were studied with mass analyzed ion kinetic energy (MIKE) spectroscopy.[30] This technique has the particular advantage over conventional mass spectrometry that it makes it possible to monitor the reactions of specific mass selected ions, rather than the collection of reactions of

TABLE 2: Calculated Heats of Formation[a] (kJ mol^{-1}, 298 K) of the Species Involved in Intramolecular 1,4- and 1,5-Hydrogen Atom Abstraction by the Amino Group in Primary Aliphatic Amine Radical Cations, RNH$_2^{+\bullet}$

	γ-distonic isomer			molecular ion				δ-distonic isomer		
R	trans	gauche[b]	TS(1,4)	gauche[b]	trans	gauche[c]	TS(1,5)	gauche[c]	trans	simple cleavage[d]
propyl	−20	−30	+59	+2	778					+95
butyl	−30	−43	+38[e]	+3	751	(+1)	(+10)	−36	−18	+102
isobutyl	−15	−24	+60	0[f]	740[f]					+103
sec-butyl	−21	−31	+57[g]	+1	734					+54, 44[h]
pentyl	−27	−40	+37	+4	727	(+1)	(−3[i])	−51	−29	+106
isopentyl	−38	−50	+26	+3	718	(+2)	(+9[j])	−33[k]	−19[l]	+109
2-methylbutyl	−16[m]	−26[m]	+57[m,n]	0[o]	717	(−4)	(+8)	−35	−19	+105
2-methylbutyl	−30[p]	−42[p]	+34[p,q]	+1[r]	717					+105
2-pentyl	−32	−45	+37[s]	+4	707	(+1)	(+11)	−36	−21	+61, 46[h]
3-pentyl	−21	−31	+57	0	707					+49
1,2-dimethylpropyl	−17	−26	+54	0[f]	698[f]					+60, 47[h]
isohexyl	−27	−41	+33	+4	697	(−1)	(−11)	−63	−36	+105

[a] $\Delta H_\mathrm{f}(\mathrm{M}^{+\bullet})$ (all-trans conformer) derived from G3 calculations; other heats of formation given relative to the molecular ion (G3(MP2) differences). Relative heats of formation given in parentheses are less securely determined, owing to possibly inaccurate estimates of zero-point vibrational energy and heat capacity (see text). [b] Conformer with one C,N gauche interaction (the conformer that more closely resembles the 1,4-H-transfer TS). [c] Conformer with one C,C and one C,N gauche interaction (the conformer that more closely resembles the 1,5-H-transfer TS). [d] Heats of formation of the products of simple cleavage of the α-C−C bond, relative to the molecular ion. [e] Methyl group equatorial in the transition state; the TS is 4 kJ mol^{-1} higher when the methyl group is axial. [f] Conformer with one CH$_3$ gauche to the NH$_2$. [g] Methyl group equatorial in the transition state; the TS is 4 kJ mol^{-1} higher when the methyl group is axial. [h] Loss of CH$_3$. [i] The twist-boat transition state is 22 kJ mol^{-1} higher in energy. [j] The twist-boat transition state is 24 kJ mol^{-1} higher in energy. [k] CH$_2^\bullet$ gauche to NH$_3^+$; the conformer with the terminal CH$_3$ closer to the NH$_3^+$ is 17 kJ mol^{-1} higher. [l] CH$_2^\bullet$ gauche to the α-CH$_2$; the conformer with the terminal CH$_3$ gauche to the α-CH$_2$ is 4 kJ mol^{-1} higher in energy. [m] 1,4-hydrogen atom abstraction from CH$_3$. [n] Ethyl group equatorial in the transition state; the TS is 3 kJ mol^{-1} higher when the ethyl group is axial. [o] CH$_3$ gauche to the NH$_2$. [p] 1,4-hydrogen atom abstraction from CH$_2$. [q] Methyl groups trans (eq,eq); the TS is 6 kJ mol^{-1} higher when the methyls are cis (ax,eq). [r] CH$_2$ gauche to the NH$_2$. [s] Both methyls equatorial; both transition states with one methyl equatorial, one axial are 3 kJ mol^{-1} higher.

TABLE 3: Calculated Heats of Formation[a] (kJ mol^{-1}, 298 K) of the Species Involved in Intramolecular 1,4- and 1,5-Hydrogen Atom Abstraction by the Amino Group in Secondary and Tertiary Aliphatic Amine Radical Cations, RNHCH$_3^{+\bullet}$ and RN(CH$_3$)$_2^{+\bullet}$

	γ-distonic isomer			molecular ion				δ-distonic isomer		
R	trans	gauche[b]	TS(1,4)	gauche[b]	trans	gauche[c]	TS(1,5)	gauche[c]	trans	simple cleavage[d]
					RNHCH$_3^{+\bullet}$					
propyl	+12	+3	+80	+3	721					+110
butyl	0	−12	+56[e]	+2	696	+2	+32	−5	+12	+115
isobutyl	+13	+4	+77	0[f]	687[f]					+114
sec-butyl	+12	+1	+75	0	679					+75, 67[g]
pentyl	+1	−10	+54	+1	673	(+1)	(+14[h,i])	−22	−1	+117
isopentyl	−7	−21	+43	+2	665	+1	+29[h]	−5	+9	+119
2-methylbutyl	+13[j]	+4[j]	+76[j]	0[k]	663[k]	+2	+30[h]	−5	+10	+117
2-methylbutyl	0[l]	−12[l]	+52[l,m]	0[n]	663					+117
					RN(CH$_3$)$_2^{+\bullet}$					
propyl	+38	+27	+94	0	677					+122
butyl	+26	+13	+73	+1	652	+5	+51	+21	+37	+125

[a] $\Delta H_\mathrm{f}(\mathrm{M}^{+\bullet})$ (all-trans conformer) derived from G3 calculations; other heats of formation relative to the molecular ion (G3(MP2) energy differences). Heats of formation given in parentheses are less securely determined, owing to possibly inaccurate estimates of zero-point vibrational energy and heat capacity (see text). [b] Conformer with one C,N gauche interaction (the conformer that more closely resembles the 1,4-H-transfer TS). [c] Conformer with one C,C and one C,N gauche interaction (the conformer that more closely resembles the 1,5-H-transfer TS). [d] Heats of formation of the products of simple cleavage of the α-C−C bond relative to the molecular ion. [e] Both methyl groups equatorial in the transition state; the TS is 3 kJ mol^{-1} higher when the C-methyl is axial. [f] Conformer with one CH$_3$ gauche to N. [g] Loss of CH$_3$. [h] Both methyl groups equatorial in the transition state. [i] The twist-boat transition state is 21 kJ mol^{-1} higher in energy. [j] 1,4-Hydrogen atom abstraction from CH$_3$. [k] CH$_3$ gauche to N. [l] 1,4-Hydrogen atom abstraction from CH$_2$. [m] The two C-methyls trans (eq,eq) in the transition state; the TS is 5 kJ mol^{-1} higher when the C-methyls are cis (ax,eq). [n] CH$_2$ gauche to N.

different ionic species that take place in mass spectrometer ion sources; furthermore, the reactions examined are those of not-very-highly energized reactant ions. The MIKE spectra used to examine the degree of H/D exchange in metastable amine radical cations were obtained on a JEOL JMS-HX110/HX110A four-sector mass spectrometer as previously described.[29]

The MIKE spectra of *N*-deuterated amines that may possibly undergo 1,4-H-atom abstraction are summarized in Table 5, to complement the considerable body of experimental results reported in the literature.[2−6,13−16,31]

Discussion

Amine Radical Cations. The calculated structure of simple primary amine radical cations was briefly described earlier.[14] The nitrogen atom is “flat”; the nitrogen atom and the three atoms bonded directly to N lie almost in the same plane. The RNCC dihedral angle involving the C(α)−C(β) bond in the lower-energy conformation of ionized primary amines is close to 90°, as was also concluded by Janovský et al.[11] This C−C bond can be unusually long (up to 1.8 Å), particularly when the α- or β-carbon atoms carry additional alkyl substituents.

TABLE 4: Calculated[a] Heats of Formation (kJ mol^{-1}, 298 K) of the Species Involved in Intramolecular 1,6-Hydrogen Atom Abstraction by the Amino Group in Amine Radical Cations

	molecular ion			ϵ-distonic ion	
	trans	gauche[b]	TS(1,6)	gauche[b]	trans
pentylamine$^{+\bullet}$	727	+9	(+18[c])	−37	−18
N-methylpentylamine$^{+\bullet}$	673	+13	+31	−8	+10
hexylamine$^{+\bullet}$	703	+5	(+7[d])	−55	−29

[a] $\Delta H_f(M^{+\bullet})$ (all-trans conformer) derived from G3 calculations; other heats of formation relative to the molecular ion (G3(MP2) energy differences). Heats of formation given in parentheses are less securely determined, owing to possibly inaccurate estimates of zero-point vibrational energy and heat capacity (see text). [b] Conformer with two C,C and one C,N gauche interaction (the conformer that more closely resembles the 1,6-H-transfer TS). [c] Twist-boat transition state 8 kJ mol^{-1} higher in energy than the chair TS. [d] Twist-boat transition state 5 kJ mol^{-1} higher in energy than the chair TS.

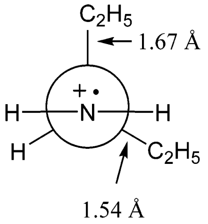


Figure 1. Newman projection of the 3-pentylamine radical cation. The central C−C bonds are of different lengths.

As an example, Figure 1 illustrates that the C−C bonds connecting the two ethyl groups to the α-carbon in 3-pentylamine are not equally long; that with a HNCC dihedral angle of 90° has a long C(α)−C(β) bond, 1.67 Å, whereas the length of the bond to the other ethyl group is 1.54 Å. The calculated bond lengths are somewhat sensitive to the theoretical method employed; Table 6 summarizes the CC distances predicted with B3LYP and MP2 geometry optimizations.

Perhaps surprisingly, the G3 energies are not very sensitive to the length of this particular bond; the heats of formation are very nearly the same (within 1 kJ mol^{-1}) regardless of whether the single-point energy calculations are based on the MP2 geometry or on the B3LYP geometry, even when these differ markedly, which suggests a quite flat potential energy surface.

Gauld and Radom[32] concluded that the long C−C bond in the ethanol radical cation is not a computational artifact, and we find no indications to suggest that the long bonds determined for amine radical cations would be artifacts. The results in Table 6 illustrate that the bond elongation is less pronounced in the radical cations of secondary and tertiary amines; our results show that neither distonic isomers of amine radical cations nor ammonium ions exhibit similarly unusual bond lengths, but remarkably long calculated α-C−C bonds were recently reported for a number of alcohol radical cations.[33−35]

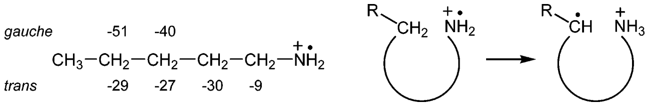


Figure 2. Heats of formation of the trans and gauche conformers of the distonic isomers of the pentylamine radical cation, in kilojoules per mole relative to the parent ion.

The heats of formation of the gauche and all-trans conformers of amine radical cations are not particularly different, in contrast to the situation for their γ- and δ-distonic isomers (discussed below).

Distonic Isomers. The heats of formation of the molecular ions of primary amines are up to 40 kJ mol^{-1} higher than the heats of formation of their β-, γ-, δ-, and ϵ-distonic isomers in the all-trans conformation (Tables 1−4). The α-distonic isomers are less stable than the other distonic ions,[36−38] which demonstrates that the interaction between the radical carbon and an adjacent ammonium nitrogen is destabilizing; possible reasons for this behavior were discussed by Mayer et al.[39] The all-trans conformers of the β-, γ-, and δ-distonic isomers of a given primary amine radical cation have approximately the same ΔH_f value (Figure 2), which suggests that in this conformation there is only moderate interaction between the ammonium group and the remote alkyl radical site. However, the situation is quite different for the gauche conformers of the γ-, δ-, and ϵ-distonic isomers (Figure 3), which are appreciably more stable than the trans forms. The enthalpy difference is 10−14 kJ mol^{-1} for γ-distonic ions and 15−27 kJ mol^{-1} for δ- and ϵ-distonic ions; the higher differences correspond to ions with tertiary radical sites (Tables 2 and 3). The gauche and trans conformers of the distonic isomers of secondary and tertiary amine radical cations exhibit similar enthalpy differences.

Apparently, in the gauche conformer of the γ-, δ-, and ϵ-distonic ions, there is a favorable interaction between the ammonium group of the distonic ion and the carbon radical site, an interaction that is not present (or not very pronounced) in

TABLE 5: MIKE Spectra of the Metastable Molecular Ions of Small Primary and Secondary Amines and Their *N*-Deuterated Analogues Capable of 1,4-H-Abstraction[a]

m/z	30	31	32	42	43	44	45	46	56	57	58	59	60	70	71	72	73
$CH_3CH_2CH_2NH_2^{+\bullet}$	**100**																
$CH_3CH_2CH_2ND_2^{+\bullet}$		24	100														
$(CH_3)_2CHCH_2NH_2^{+\bullet}$	**70**		5			100											
$(CH_3)_2CHCH_2ND_2^{+\bullet}$	25	100	54			16	94	36									
$C_2H_5(CH_3)CHNH_2^{+\bullet}$					100[b]	**4**											
$C_2H_5(CH_3)CHND_2^{+\bullet}$							100	4									
$(C_2H_5)_2CHNH_2^{+\bullet}$										100[b]	3						
$(C_2H_5)_2CHND_2^{+\bullet}$												100	3				
$(CH_3)_2CH(CH_3)CHNH_2^{+\bullet}$					100[c]	3								67		3	
$(CH_3)_2CH(CH_3)CHND_2^{+\bullet}$							100	3						48	3	3	
$CH_3CH_2CH_2NHCH_3^{+\bullet}$						**100**											
$CH_3CH_2CH_2NDCH_3^{+\bullet}$						21	100										
$(CH_3)_2CHCH_2NHCH_3^{+\bullet}$						**100**											
$(CH_3)_2CHCH_2NDCH_3^{+\bullet}$							100										
$C_2H_5(CH_3)CHNHCH_3^{+\bullet}$											**100**						
$C_2H_5(CH_3)CHNDCH_3^{+\bullet}$												100					

[a] α-Cleavage peaks in bold face; peaks less than 3% relative intensity omitted; spectra recorded at high resolution demonstrate that the [M − 17$^+$] peaks present in several MIKE spectra of primary amine molecular ions are due to the reactions of ^{13}C-containing [M − H$^+$] ions; these peaks have been omitted. [b] Expulsion of C_2H_6 (α-cleavage with concomitant H-transfer). [c] Expulsion of C_3H_8 (α-cleavage with concomitant H-transfer).

TABLE 6: Calculated C(α)−C(*β*) Bond Lengths[a] in Aliphatic Amine Radical Cations

R	calc type[b]	$RNH_2^{+\bullet}$	$RNHCH_3^{+\bullet}$	$RN(CH_3)_2^{+\bullet}$
propyl	MP2	1.58	1.55	1.54
	B3LYP	1.65	1.58	1.56
sec-butyl	MP2	1.59	1.56	1.53
	B3LYP	1.67	1.59	1.56
3-pentyl	MP2	1.59[c]	1.56[c]	
		1.52[d]	1.53[d]	
	B3LYP	1.67[c]	1.60[c]	
		1.54[d]	1.54[d]	
3-methyl-3-pentyl	MP2	1.60[c]		
		1.53[d]		
isobutyl	MP2	1.65	1.57	1.55
	B3LYP	1.71	1.61	1.58
1,2-dimethyl-propyl	MP2	1.82	1.57	
	B3LYP	1.80	1.63	
neopentyl	MP2	1.84	1.58	
	B3LYP	1.83	1.65	

[a] Values in angstroms; lower-energy conformations. [b] MP2(full)/6-31+G(d,p), B3LYP/6-31G(d). [c] HNCC dihedral angle approximately 90°. [d] HNCC dihedral angle approximately 30°.

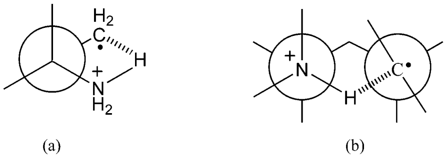


Figure 3. Newman projections of the gauche conformers of γ- and δ-distonic amine radical cations that exhibit internal hydrogen bonding.

the gauche conformer of the amine radical cation. We take the stabilization of the gauche forms to be a consequence of the presence of a C−H−N hydrogen bond. It is reasonable to expect to find hydrogen bonding in systems in which proton transfer can take place. By analogy, where hydrogen atom transfer is known to occur, it is reasonable to expect a similar phenomenon, hydrogen atom bonding, an advance as it were on the hydrogen atom transfer.

The calculated properties of the gauche forms agree well with what is expected[40] for species with pronounced intramolecular hydrogen bonding, with regard to stabilization, bond lengths, and vibrational frequencies. Taking the δ-distonic isomer of pentylamine as an example, the N−H bond involved is noticeably elongated, from 1.026 to 1.054 Å (B3LYP/6-31G-(d) calculations); the distance between the hydrogen atom and the acceptor carbon atom is 2.03 Å, to compare with 2.65 Å for the analogous distance in the corresponding conformer of the 2-hexyl radical. Furthermore, the calculated vibrational frequency of the appropriate N−H stretch is considerably lowered, from ~3500 to ~3000 cm^{-1} (B3LYP/6-31G(d) calculations, unscaled; the vibrational frequencies calculated with MP2 methods bring out this point less clearly).

The difference in energy between the gauche and trans conformers of γ- and δ-distonic amine ions was first noted by Yates and Radom;[18] similar observations were made by Bouchoux and co-workers[33] for two distonic isomers of primary alcohol radical cations and by Semialjac[41] for a distonic isomer of valeramide. Our current studies confirm that stabilization by intramolecular hydrogen bonding of the gauche conformers significantly influences the properties of straight-chain as well as branched γ- and δ-distonic isomers of alcohol, ether, aldehyde, ketone, and carboxylic acid radical cations.

The heats of formation of secondary amine radical cations are not very different from the heats of formation of their distonic isomers (Table 3). The intramolecular hydrogen atom abstraction from tertiary carbon leads to more stable isomers, whereas distonic isomers of secondary amine radical cations formed by hydrogen atom abstraction from methyl groups are higher in energy than the initial radical cation. Distonic isomers of tertiary amine radical cations are higher in energy than the corresponding ionized amines; extrapolation of the results in Tables 2 and 3 suggests that a possible exception would be the gauche conformer of a δ-distonic ion formed by abstraction of hydrogen from a tertiary carbon atom. Calculations with reduced basis sets (CBS-q)[42] indicate that this is indeed the case for ionized 4-methyl-*N*,*N*-dimethylpentylamine, but systematic examination of systems of that size (several conformers of $C_8H_{19}N^{+\bullet}$ or larger species) at the G3(MP2) level is beyond our current computational resources.

SCHEME 4

$$RNH_2^{+\bullet} + H^\bullet \longrightarrow RNH_3^+$$

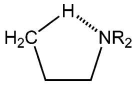
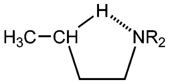
Isomerization. The barriers to intramolecular 1,2- and 1,3-hydrogen atom transfer in amine radical cations are relatively high (Table 1), and these reactions are not expected to compete successfully with the dissociation reactions of the ionized amines (discussed below), nor with intramolecular hydrogen atom abstraction reactions with larger transition states. Chain-length permitting, the preferred H-atom transfer is a 1,5-shift, involving a six-center cyclic transition state, as expected by analogy to the McLafferty rearrangement and other hydrogen abstraction reactions of gas-phase radical cations[43] as well as to the reactions of amine radical cations in the condensed phase.[8,9,11] However, it has been reported that hydrogen atom transfer in imine radical cations in low-temperature matrixes takes place via a five-membered cyclic transition state.[44]

It is to be expected that nearly all long-lived primary amine radical cations with sufficient internal energy to react at all will isomerize to the corresponding γ- or δ-distonic isomers (or to isomers formed by abstraction of even more distant hydrogen atoms), inasmuch as the conversion is an exothermic reaction, and as the barriers to hydrogen atom transfer are moderate (see below). Furthermore, the distonic ions may isomerize further, by carbon-to-carbon hydrogen atom transfer or by skeletal rearrangement.[2−4,13−16] The gas-phase reactions of not highly energized primary amine radical cations will in turn reflect the structure and properties of (possibly several different) isomerized species, not those of the ions formed by the initial electron ionization. This is in good agreement with the results of the neutralization−reionization experiments described by Wesdemiotis et al.,[5] and it is further illustrated by the observation that the unimolecular fragmentation reactions of long-lived primary amine molecular ions[2,3] as well as those of low-energy, low-temperature molecular ions[45] are quite different from the reactions that the standard 70 eV electron ionization mass spectra reflect.

In contrast, most of the long-lived molecular ions of secondary and (particularly) tertiary amines may well retain their initial structure, inasmuch as isomerization via H-atom abstraction is only marginally favorable (if at all), and experiment bears this out: most reactions that the long-lived molecular ions of N-substituted amines undergo are also observed for the ions that react in the mass spectrometer ion source.[13,29,31,46]

The results in Tables 2 and 3 allow us to compare the hydrogen atom affinity (HA) of primary, secondary, and tertiary amine radical cations. The HA is defined as the negative of the enthalpy change of the reaction shown in Scheme 4, and it is possible to derive relative hydrogen atom affinities of long-chain amine radical cations from the heat of reaction of the

TABLE 7: Selected Properties of 1,4-H-Atom Transfer Transition States[a]

R,R	C−H	N−H	CHN	E_0	ΔH_r
$CH_3CH_2CH_2NR_2^{+\bullet}$ 					
H,H	1.21	1.53	125	59	−30
H,CH_3	1.24	1.44	130	80	+3
CH_3,CH_3	1.26	1.39	133	94	+27
n-$C_4H_9^{\bullet}$	1.35		133[b]	102	0
$CH_3CH_2CH_2CH_2NR_2^{+\bullet}$ 					
H,H	1.19	1.62	123	38	−43
H,CH_3	1.22	1.51	128	56	−12
CH_3,CH_3	1.24	1.44	132	73	+13
n-$C_5H_{11}^{\bullet}$	1.34[c]		134[b]	95	−11

[a] UMP2/6-31+G(d,p) calculations; bond lengths in angstroms, angles in degrees, heats of reaction and critical energies in kilojoules per mole (from Tables 2 and 3). Data for 1,4-H-atom transfer in alkyl radicals included for comparison. [b] CHC angle. [c] Two C−H distances in TS, 1.34, 1.36 Å.

intramolecular H-atom abstraction (Figure 2), taking the C−H bond dissociation energy at remote positions to be the same for long-chain primary, secondary, and tertiary amines.[38] The results suggest that the difference[47] between the hydrogen atom affinities of primary and secondary amine radical cations is 30 ± 3 kJ mol^{-1}, and the difference between the HA of secondary and tertiary amines is 25 ± 5 kJ mol^{-1}. These differences agree only moderately well with those given by Lias et al.[48]

1,4-Hydrogen Atom Abstraction. The calculated structure of the five-membered cyclic transition state typically resembles a flattened cyclopentane envelope. Representative CHN angles and C−H and N−H bond lengths of the 1,4-hydrogen atom transfer transition state are listed in Table 7; they illustrate that the transition states are quite far from symmetrical and resemble the amine radical cation rather than the distonic product ion. For the migrating hydrogen atom, the distance to the carbon atom is considerably shorter than the distance to the nitrogen atom; it is also shorter than the C−H distance in the transition state for intramolecular 1,4-H-atom transfer in neutral *n*-butyl and *n*-pentyl radicals (Table 7). The CHN angle in the transition state is somewhat smaller for the exothermic H-transfer in primary amines than for the endothermic H-transfer in tertiary amine radical cations. In the latter case, the CHN angle is close to the CHC angle calculated for the butyl and pentyl radical transition states. Transition states with additional alkyl substituents at C or N in the pseudoequatorial position are in most cases 4−5 kJ mol^{-1} lower in energy than those with pseudoaxial substituents. The α-C−C bonds assume normal lengths in the transition state for hydrogen atom transfer, also in those instances where the ground state reactant ion exhibits an elongated α-C−C bond.

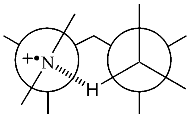


Figure 4. Newman projection of the transition state for the reversible 1,5-H-atom transfer that serves to interconvert the butylamine radical cation and the corresponding δ-distonic isomer (cf. Table 8).

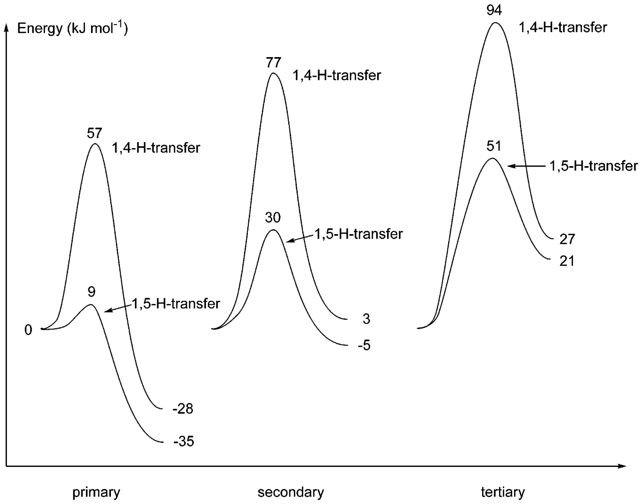


Figure 5. Average critical energies and heats of reaction for the 1,4- and 1,5-hydrogen atom abstraction from terminal methyl groups in primary, secondary, and tertiary amine radical cations.

The enthalpy barriers toward 1,4-H-atom transfer are lower for primary amine radical cations than for secondary or tertiary ones (Table 7); 1,4-abstraction of a tertiary hydrogen atom by $-NH_2^{+\bullet}$ requires only about 25 kJ mol^{-1}. Higher barriers are encountered when the hydrogen atom is abstracted by a secondary or tertiary amine nitrogen, and when abstraction takes place at a CH_3 group (Tables 2 and 3); 1,4-abstraction of a methyl hydrogen by $-N(CH_3)_2^{+\bullet}$ requires nearly 100 kJ mol^{-1}. For comparison, we find the barriers for 1,4-hydrogen atom abstraction in the *n*-butyl and *n*-pentyl radicals to be 102 and 95 kJ mol^{-1}, respectively.

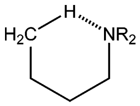
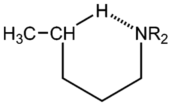
The higher barriers for abstraction of methyl hydrogen atoms are reflected in the H/D-exchange results reported by Audier,[3] who found that the hydrogen atoms of the methyl substituent in 2-methylbutylamine and 2-methylpentylamine were only involved in exchange with the amino group hydrogen atoms to a very limited extent, in contrast with the hydrogen atoms of the methylene groups. The results of EPR studies[11] of the 1,4-hydrogen atom transfer that converts ionized propylamine to its γ-distonic isomer strongly suggest that tunneling can be important for these reactions.

1,5-Hydrogen Atom Abstraction. The computational results suggest that the lower-energy transition state for 1,5-hydrogen atom abstraction will have a chairlike geometry (Figure 4). We have in several instances located also a twist-boat transition state for the 1,5-H-transfer to nitrogen in amine radical cations; there are enthalpy differences of 20−25 kJ mol^{-1} between the chair and twist-boat transition states, and it is in turn not likely that the boat-type transition states will much influence the overall course or rate of reaction.

The 1,5-transfer transition states are quite reactant-like; representative CHN angles and C−H and N−H bond lengths are included in Table 8. As observed for the 1,4-transfer transition state, the CHN angle is substantially smaller in the transition state of the exothermic reactions of primary amines than in the transition state of the reactions of tertiary amines or alkyl radicals. The 1,5-transfer transition states are even less symmetrical than those for 1,4-transfer, with a quite short C−H bond and a quite long N−H bond. As expected, transition states with additional alkyl groups at C or N in the equatorial position are lower in energy than those with axial substituents, but the difference is only a few kilojoules per mole.

The enthalpy barriers toward 1,5-shifts are lower than those toward 1,4-shifts (Tables 2 and 3), ranging from 50 kJ mol^{-1} for H-atom abstraction in tertiary amine radical cations to almost

TABLE 8: Selected Properties of 1,5-H-Atom Transfer Transition States[a]

R,R	C−H	N−H	CHN	E_0	ΔH_r
$CH_3CH_2CH_2CH_2NR_2^{+\bullet}$ 					
H,H	1.16	1.62	142	(10)	−36
H,CH_3	1.19	1.49	150	32	−5
CH_3,CH_3	1.21	1.42	154	51	+21
n-$C_5H_{11}^{\bullet}$	1.33		153[b]	73	0
$CH_3CH_2CH_2CH_2CH_2NR_2^{+\bullet}$ 					
H,H[c]	1.15	1.74	138	(0)	−51
H,H[d]	1.24	1.48	143	(19)	−51
H,CH_3[c]	1.17	1.58	147	(14)	−22
H,CH_3[d]	1.27	1.40	147	35	−22
n-$C_6H_{13}^{\bullet}$	1.32[e]		155[b]	65	−10

[a] UMP2/6-31+G(d,p) calculations; bond lengths in angstroms, angles in degrees, heats of reaction and critical energies in kilojoules per mole (from Tables 2 and 3). Data for 1,5-H-atom transfer in alkyl radicals included for comparison. [b] CHC angle. [c] Chair TS. [d] Twist-boat TS. [e] Two C−H distances in TS, 1.32, 1.34 Å.

nothing for H-transfer in primary amine radical cations (discussed in more detail below).

The results in Table 2 show that the 1,5-H-transfer transition state for primary amine radical cations is not much higher in energy than the reactant gauche conformer; that is to say, there is hardly any enthalpy barrier toward hydrogen atom transfer to the nitrogen atom. The harmonic approximation cannot be expected to be adequate in such instances, when the potential energy surface is very flat, which complicates the calculation of zero-point vibrational energy and integrated heat capacity of the relevant stationary points, and in turn the accurate calculation of the magnitude of the enthalpy barriers. Taking only the electronic energy into account, it appears that there is in most cases a small enthalpy barrier toward 1,5-H-atom transfer, typically ∼20 kJ mol^{-1} when abstraction is from CH_3, which is of the same order of magnitude as the energy of the vibration that becomes the reaction coordinate in the transition state (a C−H or N−H stretch). However, including the zpve and C_p contributions determined with simple methods can lead to the somewhat paradoxical result that the enthalpy of formation of the transition state is lower than that of the reactant.

A quite detailed analysis would be required in order to accurately estimate the zpve and heat capacity contributions in these cases. At the limited level of sophistication of the methods employed in the present study, it can only be concluded that the barrier to 1,5-hydrogen atom transfer in primary amine radical cations is quite small and that we cannot accurately establish the exact location and energy of the transition state when primary amine radical cations isomerize in this manner. Computational studies of H-atom abstraction in secondary and tertiary amine radical cations are in most cases not similarly problematic, inasmuch as the enthalpy barriers involved are generally considerably higher.

Comparisons. The enthalpy barriers for H-atom abstration in primary amine radical cations calculated in the present study are slightly lower than the barriers calculated by Bouchoux and co-workers[33] for H-atom abstraction in primary alcohol radical cations. The experimental results reported by Wesdemiotis et al.[5] led these authors to a similar conclusion, that the enthalpy barriers toward H-atom abstraction are lower for amine radical cations than for alcohol radical cations, even though the H-abstraction is more exothermic in the latter case.

The extensive H/D exchange observed[6] in deuterium labeled long-chain primary amine radical cations predominantly involves the hydrogen atoms initially located at N and at the 4-, 5-, and 6-positions of the alkyl chain. In other words, when the alkyl chain is sufficiently long, H-atom exchange between N and C3 (1,4-shift) becomes relatively less important than exchange between N and methylene groups further removed from the nitrogen, via six-membered, seven-membered, and eight-membered cyclic transition states. We find that the energetics of 1,6-H-atom transfer in the pentyl- and hexylamine radical cations very much resembles that of the 1,5-H-atom transfer (Table 4).

Compared to primary amines, H/D exchange in long-chain *N*-deuterated secondary amine radical cations is less extensive,[13,31] probably reflecting that the enthalpy barriers for hydrogen atom abstraction are on average some 20 kJ mol^{-1} higher in the presence of *N*-alkyl groups (Tables 2 and 3) and that these groups introduce additional conformational complications. It was suggested[31] that the hydrogen atom abstraction in these ions involves predominantly six- and seven-membered transition states.

Competition between H-Abstraction and C−C Cleavage. To assess the importance of intramolecular hydrogen atom abstraction reactions in aliphatic amine radical cations, it is useful to compare the enthalpy requirements of the H-atom transfer to the requirements of other possible gas-phase reactions in these systems, in particular the simple cleavage of the α-C−C bond. The calculated barriers to 1,2- and 1,3-H-transfer (Table 1) are nearly without exception higher than the energy required for simple cleavage, and H-atom transfer to nitrogen from the α- and *β*-carbon atoms should therefore not compete efficiently with C−C cleavage. Experiment bears that out; we find that H/D exchange does not precede C−C cleavage in, for example, the radical cations of *N*,*N*-D_2-ethylamine or *N*,*N*-D_2-isopropylamine, which expell methyl radicals with no deuterium incorporation. Related observations were made by Wesdemiotis et al.[5] and by Janovský et al.[11]

1,4-H-atom transfer requires less energy than does C−C cleavage when the amino group is bonded to a primary alkyl group (Tables 2 and 3), whereas there is only little difference in this respect between the two reactions when the amine is branched at the α-carbon atom. This is reflected in the results of deuterium labeling experiments: the metastable N-deuterated propylamine, isobutylamine, and *N*-methylpropylamine radical cations undergo exchange of carbon-bonded and nitrogen-bonded hydrogen atoms prior to unimolecular fragmentation, and fragmentation therefore leads to expulsion of deuterium-containing alkyl radicals. Conversely, H/D exchange does not precede the fragmentation of the *N*-deuterated *sec*-butylamine and *N*-methyl-*sec*-butylamine radical cations (Table 5), because C−C cleavage at the branching point is the more rapid reaction. We note that the H/D exchange prior to C−C bond cleavage is considerably more extensive for isobutylamine than for propylamine radical cations, even though the barriers involved are not very different for these two ions. This could well reflect that the lower-energy conformation of ionized propylamine possesses a trans backbone, whereas in isobutylamine one methyl group is necessarily gauche to the $-NH_2$.

Conclusions

The energetics of the intramolecular hydrogen atom abstraction and exchange in amine radical cations derived from the present computational results successfully predicts when the intramolecular CH/NH exchange will precede fragmentation by C−C bond cleavage in the gas phase. The hydrogen atom abstraction yields distonic isomers of the molecular ions, which is the initial step in the skeletal rearrangement reactions that often precede the fragmentation of metastable amine radical cations. Most long-lived primary amine molecular ions will be present as their distonic isomers, inasmuch as the isomerization is exothermic and the intermediate energy barriers are quite low. Ionized secondary and tertiary amines also undergo isomerization to their distonic counterparts, but for these ions this reaction is not similarly favorable, and many or most long-lived ions may well retain the connectivity of the parent amine. However, when less energy demanding than simple cleavage, H-atom transfer may still initiate skeletal rearrangement.

The ab initio results suggest that the gauche conformers of the γ-, δ-, and ϵ-distonic amine radical cation isomers exhibit intramolecular C−H−N hydrogen bonding that significantly lowers the heat of formation of these conformers and significantly modifies the bond lengths and infrared stretching vibrations; these results suggest that alkyl radicals can be hydrogen bond acceptors.

The intramolecular 1,5- and 1,6-H-atom transfers can take place via chair as well as twist-boat-type transition states; the critical energy for reaction via the latter is 20−25 kJ mol^{-1} higher. The unusually long C−C bonds that many of the reactant amine radical cations possess assume “normal” lengths in the transition states for H-atom transfer.

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