# Gas-Phase Reactivity of Hydroxylamine toward Charged Electrophiles. A Mass Spectrometric and Computational Study of the Protonation and Methylation of H<sub>2</sub>NOH

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The gas-phase proton affinity (PA) of H<sub>2</sub>NOH evaluated by the FT-ICR "bracketing" technique and by the kinetic method based on the unimolecular fragmentation of proton-bound adducts amounts to 193.7  $\pm$  2 kcal mol<sup>-1</sup> at 298 K, in excellent agreement with the 193.8 kcal mol<sup>-1</sup> PA computed at the GAUSSIAN 1 level of theory for the N atom, consistent with the view that N protonation is energetically favored. The computed PAs of the N atom of CH<sub>3</sub>NHOH and H<sub>2</sub>NOCH<sub>3</sub>, *i.e.* 203.9 and 201.0 kcal mol<sup>-1</sup>, respectively, agree also with the values from FT-ICR equilibrium measurements, 205.1  $\pm$  2 and 202.7  $\pm$  2 kcal mol<sup>-1</sup>, respectively, whereas the PAs calculated for the O atom are much lower, 175.1 and 179.8 kcal mol<sup>-1</sup>, respectively. Methylation of H<sub>2</sub>NOH by (CH<sub>3</sub>)<sub>2</sub>Cl<sup>+</sup> ions gives a charged product whose structure, assayed by MIKE and CAD spectrometry, indicates predominant, if not exclusive, N alkylation. The relative reactivities of the N and the O atom of H<sub>2</sub>NOH in gas-phase protonation and methylation are compared, and the observed site selectivity of (CH<sub>3</sub>)<sub>2</sub>Cl<sup>+</sup> is discussed.

#### Introduction

The study of the reactivity of hydroxylamine toward charged electrophiles is of interest in order to assess the effects of the electron-withdrawing oxygen atom upon the basicity/nucleo-philicity of the nitrogen atom of H<sub>2</sub>NOH, with respect to the unsubstituted NH<sub>3</sub> molecule, and conversely the increase of the basicity/nucleophilicity of the oxygen atom of H<sub>2</sub>NOH with respect to the unsubstituted H<sub>2</sub>O molecule.

The problem has been addressed by theoretical methods, and the results of ab initio calculations at the 4-31G\*//MP4SDQ/ 6-31G\*\* level of theory on the site proton affinity (PA) of H<sub>2</sub>-NOH show that the N atom is more basic than the O atom, the computed PAs being 199.5 and 175.2 kcal mol<sup>-1</sup>, respectively.<sup>1</sup> The result is consistent with earlier ab initio calculations, leading to a PA difference of 23 kcal mol<sup>-1,2</sup> The experimental evidence is scant, however, and restricted to the condensed phases, where the intrinsic basicity can be affected by differential solvation and other types of molecular interactions. In any case, the higher basicity of the N atom is qualitatively supported by matrix-isolation studies, showing that a strong N-HF bond exists in the H<sub>2</sub>NOH/HF complex,<sup>3,4</sup> and by the firmly established notion that hydroxylamine is a nitrogen base in solution.<sup>5</sup> In this work we aim at extending the experimental study to the gas phase, in order to establish a direct quantitative link with theory. To this end, we have undertaken to measure the gasphase PA of H<sub>2</sub>NOH with complementary experimental techniques, namely, FT-ICR, MIKE, and CAD spectrometry, comparing the results with those of high-level ab initio calculations on the relative stability of the two conceivable protomers

$$H_3 NOH H_2 NOH_2$$
  
1 2

The theoretical methods were employed to gather independent support of the experimental results, in view of the problems

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sometimes associated with positive structural discrimination by MIKE and CAD spectrometry among species, such as 1 and 2, which differ exclusively as to the location of a single H atom.

Since, however, it appeared highly desirable to gather supporting experimental evidence on the relative reactivity of the N and the O atoms of hydroxylamine toward charged electrophiles, the study has been extended to gas-phase methylation, utilizing the reaction

$$H_2NOH + (CH_3)_2Cl^+ \rightarrow CH_3Cl + [(H_2NOH)CH_3]^+$$
(1)

and probing the structure of the alkylated products by CAD and MIKE spectrometry. The choice of reaction 1 has been based on the mild and selective character of the electrophile and on the fact that protonation of CH<sub>3</sub>NHOH and H<sub>2</sub>NOCH<sub>3</sub> gives model ions having the same C, N, O connectivity as the two conceivable isomers from (1).

$$(CH_3NHOH)H^+ (H_2NOCH_3)H^+$$
3 4

Furthermore, the simple nature of 3 and 4, which contain only three atoms other than H, allows application of high-level *ab initio* methods in order to obtain theoretical evidence of their stability.

#### Results

**PA Measurements.** The equilibrium method<sup>6</sup> is not suitable in the case of H<sub>2</sub>NOH, which undergoes decomposition on the metal surfaces in the inlet system and in the ion source of the mass spectrometer. The decomposition rate can be kept sufficiently low to allow recording the EI or CI mass spectra of H<sub>2</sub>NOH; for example, the protonated molecule can be readily obtained in the external ion source of a FT-ICR spectrometer *via* the general process

$$H_2NOH + AH^+ \rightarrow (H_2NOH)\dot{H}^+ + A$$
(2)

However, the major decomposition product,  $NH_3$ , is sufficiently basic to disturb the equilibrium between  $H_2NOH$  and

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**Figure 1.** Logarithmic plot of the intensity of the (H<sub>2</sub>NOH)H<sup>+</sup> ion vs the reaction time: B = HCOOCH<sub>3</sub> ( $\Box$ ), (CH<sub>3</sub>)<sub>2</sub>O ( $\bullet$ ), (CH<sub>3</sub>)<sub>2</sub>CO ( $\circ$ ), CH<sub>3</sub>COOC<sub>2</sub>H<sub>5</sub> ( $\blacksquare$ ). Pressure of bases, corrected for the manometer response, is 3.2 × 10<sup>-9</sup> Torr.

the reference base, acting as an efficient proton sink at the long reaction times necessary to evaluate the equilibrium constant.

We have therefore applied the "bracketing" technique,<sup>6</sup> measuring the rate of proton-transfer reactions from protonated hydroxylamine to selected bases.

$$(H_2NOH)H^+ + B \rightarrow H_2NOH + BH^+$$
(3)

To this end, protonated hydroxylamine, formed in the external ion source of the FT-ICR spectrometer, has been transferred into the resonance cell and allowed to react with a suitable reference base, B, in the absence of impurities. The rate of (3) decreases from  $(2.8 \pm 0.5) \times 10^{-9}$  cm<sup>3</sup> s<sup>-1</sup> molecule<sup>-1</sup> at 300 K when B = CH<sub>3</sub>COOC<sub>2</sub>H<sub>5</sub>, PA = 198.1 kcal mol<sup>-1,6</sup> to 1.1  $\times 10^{-9}$ cm<sup>3</sup> s<sup>-1</sup> molecule<sup>-1</sup> when B = (CH<sub>3</sub>)<sub>2</sub>CO, PA = 193.7 kcal mol<sup>-1,7</sup> to 3.7  $\times 10^{-10}$  cm<sup>3</sup> s<sup>-1</sup> molecule<sup>-1</sup> when B = (CH<sub>3</sub>)<sub>2</sub>O, PA = 189.6 kcal mol<sup>-1,7</sup> becoming very low, ca. 6.5  $\times 10^{-11}$  cm<sup>3</sup> s<sup>-1</sup> molecule<sup>-1</sup> when B = HCOOCH<sub>3</sub>, PA = 188.1 kcal mol<sup>-1</sup> (see Figure 1).<sup>6</sup>

Such a trend leads to an estimated  $PA(H_2NOH) = 193 \pm 4$  kcal mol<sup>-1</sup>. The large uncertainty range has been reduced using the kinetic method<sup>8</sup> based on the unimolecular decomposition of proton-bound adducts obtained from appropriate gas mixtures in the CI ion source of a ZAB-2F mass spectrometer.

$$(B_1 - H - B_2)^+ - - - - - B_1 H^+ + B_2$$
(4a)  
$$B_1 + B_2 H^+$$
(4b)

Denoting H<sub>2</sub>NOH as B<sub>1</sub>, the MIKE spectra of selected adducts show that only process 4a occurs when B<sub>2</sub> =  $(CH_3)_2O$  and only process 4b takes place when B<sub>2</sub> =  $CH_3COOC_2H_5$ , whereas both processes occur at the same rate when B<sub>2</sub> =  $(CH_3)_2CO$ , as illustrated in Figure 2. These results show that the PA of H<sub>2</sub>-NOH is very close to that of  $(CH_3)_2CO$  and hence amounts to 193.7 kcal mol<sup>-1</sup>, with an estimated uncertainty of ±2 kcal mol<sup>-1</sup>.

The methylhydroxylamines are both sufficiently stable to allow application of the FT-ICR equilibrium method. Preliminary "bracketing" experiments have suggested that  $C_2H_5O$ -t- $C_4H_9$ , PA = 205.3 kcal mol<sup>-1</sup>,<sup>6</sup> is a suitable reference base for evaluating the prototropic equilibrium,

$$(CH_3NHOH)H^+ + C_2H_5O-t-C_4H_9 \Longrightarrow$$
  
 $CH_3NHOH + (C_2H_5O-t-C_4H_9)H^+ (5)$ 



**Figure 2.** Typical MIKE spectrum of the  $[(CH_3)_2CO-H-H_2NOH]^+$  proton-bound adduct.



**Figure 3.** Time dependence of the relative intensities of the (CH<sub>3</sub>-ONH<sub>2</sub>)H<sup>+</sup> ( $\Box$ ) and (CH<sub>3</sub>CO-*t*-C<sub>4</sub>H<sub>9</sub>)H<sup>+</sup> ( $\bullet$ ) ions at 298 K, under a total pressure of 2.3 × 10<sup>-8</sup> Torr, in a 1:1 CH<sub>3</sub>ONH<sub>2</sub>/CH<sub>3</sub>CO-*t*-C<sub>4</sub>H<sub>9</sub> mixture.

From two independent sets of experiments performed at different concentration ratios we obtain  $\Delta G^{\circ}_{5} = -0.15 \pm 0.04$  kcal mol<sup>-1</sup> at 298 K, and, hence, assuming  $\Delta S^{\circ}_{5} \sim 0$ , PA(CH<sub>3</sub>-NHOH) = 205.1  $\pm$  2 kcal mol<sup>-1</sup>. From the evaluation of the analogous equilibrium, illustrated in Figure 3,

$$(H_2NOCH_3)H^+ + CH_3CO-t-C_4H_9 \rightleftharpoons$$
$$H_2NOCH_3 + (CH_3CO-t-C_4H_9)H^+ (6)$$

we obtain  $\Delta G^{\circ}_{6} = +0.45 \pm 0.05$  kcal mol<sup>-1</sup> at 298 K, and, hence, based on the known PA of CH<sub>3</sub>CO-*t*-C<sub>4</sub>H<sub>9</sub>,<sup>6</sup> PA(H<sub>2</sub>-NOCH<sub>3</sub>) = 202.7 \pm 2 kcal mol<sup>-1</sup>.

**MIKE and CAD Spectrometry.** The MIKE spectrum of the ionic population from reaction 1, denoted as A, is compared in Table 1 with those of the model ions B from the protonation of CH<sub>3</sub>NHOH and of model ions C from the protonation of H<sub>2</sub>NOCH<sub>3</sub>. The spectra B and C are clearly different and largely insensitive to changes of the exothermicity of the protonation process, which spans over a range of some 65 kcal mol<sup>-1,6</sup> The MIKE spectrum of (CH<sub>3</sub>NHOH)H<sup>+</sup> displays two Gaussianshaped metastable peaks, the larger one at m/z = 30 likely arising from the loss of H<sub>2</sub>O. The intensity of the minor peak at m/z = 31 tends to increase when the parent ion is obtained from reactions of lower exothermicity. The population of (H<sub>2</sub>-NOCH<sub>3</sub>)H<sup>+</sup> model ions C displays as well two Gaussian-shaped peaks, the larger one at m/z = 18 probably arising from the

TABLE 1: MIKE Spectra of the CH<sub>6</sub>NO<sup>+</sup> Ions from the Methylation of Hydroxylamine and from the Protonation of Model Molecules

			relative intensity of fragments (%) $m/z =$			
ion	source of the ion	experimental approach	18	30	31	
A	$(CH_3)_2Cl^+ + H_2NOH$	CH <sub>3</sub> Cl/CI of H <sub>2</sub> NOH		81.4	18.6	
в	$H_3^+ + CH_3NHOH$	H <sub>2</sub> /CI of CH <sub>3</sub> NHOH		98.1	1.9	
	CH <sub>5</sub> <sup>+</sup> , C <sub>2</sub> H <sub>5</sub> <sup>+</sup> + CH <sub>3</sub> NHOH	CH₄/CI of CH <sub>3</sub> NHOH		97.1	2.9	
	$H_3O^+ + CH_3NHOH$	H <sub>2</sub> O/CI of CH <sub>3</sub> NHOH		94.5	5.5	
C	$CH_5^+, C_2H_5^+ + H_2NOCH_3$	CH <sub>4</sub> /CI of H <sub>2</sub> NOCH <sub>3</sub>	67.8		32.2	
	$H_3O^+ + H_2NOCH_3$	H <sub>2</sub> O/CI of H <sub>2</sub> NOCH <sub>3</sub>	72.6		27.1	

TABLE 2: CAD Spectra of  $CH_6NO^+$  Ions from the Methylation of  $H_2NOH$  and from the Protonation of Model Molecules

	relative intensity of fragments (%)					
m/z	A <sup>a</sup>	В	С			
33	16.3	13.5	13.7			
32	13.1	13.0	28.2			
29	12.9	13.9	25.5			
28	46.3	48.6	5.8			
17	3.0	2.6	19.4			
16	1.6	1.7	2.2			
15	4.7	4.6	4.2			
14	2.1	2.1	1.0			

<sup>a</sup> The formation processes of ionic populations A, B, and C are the same as in Table 1.

loss of CH<sub>2</sub>O, accompanied by a smaller fragment at m/z = 31. The population A of [H<sub>2</sub>NOH]CH<sub>3</sub><sup>+</sup> ions from reaction 1 is characterized by a MIKE spectrum similar to that of model ions B, except for the somewhat larger intensity of the fragment at m/z = 31. The absence of the fragment at m/z = 18 is structurally informative, pointing to the different C, N, O connectivity of ions A and C, since the fragment is the most abundant one from the metastable decomposition of ions C. In summary, the evidence from MIKE spectrometry is that the ions from reaction 1, or at least those that undergo metastable fragmentation, are methylated at the amino group.

This inference is supported by the CAD spectra of the ionic populations of interest, reported in Table 2. Whereas the CAD spectra of ions A from reaction (1) and of the model ions B are nearly superimposable, they are entirely different from the spectrum of model ions C from the protonation of  $H_2NOCH_3$ . Such results are particularly significant, since CAD spectrometry is generally believed to be much less affected than MIKE spectrometry by the internal energy content of the ions being assayed, and hence its results can be regarded as more generally representative of the isomeric composition of the ionic populations of interest.

In summary, the mutually supporting MIKE and CAD results suggest that when subjected to structural analysis, *i.e.* some  $10^{-5}$  s after its formation, the ionic population from reaction 1 contains the N-methylated isomer **3** as the predominant, if not the only, component.

**Computational Results.** The geometries of the species of interest, computed at the MP2(FU)/6-31G\* post-SCF level of theory, are illustrated in Figures 4 and 5. All of these species, with the exception of the transition state, denoted TS, correspond to true minima, as shown by examination of the relevant vibration frequencies. The G1 energies of the species of interest are reported in Table 3. From these data, and the computed geometries and vibrational frequencies, we derive the PA of  $H_2NOH$  at 298 K, 193.8 kcal mol<sup>-1</sup> for protonation at the N

atom, in excellent agreement with the experimental PA of 193.7  $\pm$  2 kcal mol<sup>-1</sup>, whereas the site PA of the O atom is computed to be 167.4 kcal mol<sup>-1</sup> at 298 K.

The search of the N-methylated and O-methylated forms of hydroxylamine has led to the identification of ions 3a and 4a, the former computed to be more stable by 29.1 kcal  $mol^{-1}$  at 298 K, according to the data of Table 3. From Figure 4, the N-O, N-C, and O-C distances in the above ions are not significantly larger than the distances in the corresponding neutral species, and therefore cations 3a and 4a cannot be characterized as ion-molecule complexes. From Table 3, the PA at 298 K of the N and O atom can be computed to be 203.9 and 175.1 kcal mol<sup>-1</sup> for CH<sub>3</sub>NHOH and 201.0 and 179.8 kcal  $mol^{-1}$  for H<sub>2</sub>NOCH<sub>3</sub>, respectively. On the basis of the calculated energies of CH<sub>3</sub><sup>+</sup>, H<sub>2</sub>NOH, and ions 3a and 4a, we have also evaluated the methyl cation affinity (MCA) of the N and O atom of hydroxylamine, which amount to 101.4 and 72.3 kcal mol<sup>-1</sup> at 298 K, respectively, at the G1 level of theory.

Finally, the problem related to the interconversion of ion **3a** to **4a** has been addressed. The structure TS possesses only one imaginary frequency (822i cm<sup>-1</sup>). From the examination of the corresponding normal mode of vibration, this species connects ion **3a** to **4a** via the in-plane motion of the migrating methyl group. From Table 3, intramolecular isomerization is characterized as a high-energy process, since the stability difference at 0 K between **3a** and TS is as large as  $67.2 \text{ kcal mol}^{-1}$  at the G1 level. The picture outlined by the theoretical study of the ionic methylation of H<sub>2</sub>NOH is illustrated in the diagram of Figure 6.

### Discussion

The experimental and theoretical results concur in outlining a consistent picture of the gas-phase reactivity of hydroxylamine toward charged electrophiles, showing that the N atom is the preferred nucleophilic center in the protonation and cationic alkylation of the ambident substrate. The PA of the N atom computed at the G1 level of theory, 193.8 kcal mol<sup>-1</sup>, is very close to the experimental value of the PA of H<sub>2</sub>NOH, 193.7  $\pm$ 2 kcal mol<sup>-1</sup>, whereas the PA of the O atom is computed to be lower by 26.4 kcal mol<sup>-1</sup>. Both the PA values are somewhat lower than those previously computed at the 4-31G\*/MP4SDQ/ 6-31G\*\* level of theory, 199.5 and 175.2 kcal mol<sup>-1</sup> for the PA of the N and the O atom, respectively,<sup>1</sup> but the  $\Delta$ PA difference is nearly the same at the two levels.

The agreement between theory and experiment is also satisfactory in the case of methylhydroxylamines. The theoretically calculated PAs of the N atom of CH<sub>3</sub>NHOH and of H<sub>2</sub>-NOCH<sub>3</sub>, 203.9 and 201.0 kcal mol<sup>-1</sup>, respectively, compare well with the experimentally measured PAs of the two bases, 205.1  $\pm$  2 and 202.7  $\pm$  2 kcal mol<sup>-1</sup>, respectively.

Comparison of the PA of appropriate pairs of bases allows one to evaluate the effect of the substituents on the basicity of the N and the O atom of hydroxylamine. The PA of NH<sub>3</sub> decreases by ca. 10 kcal mol<sup>-1</sup> upon replacement of one of the H atoms by the OH group, and a similar effect is noted in the case of CH<sub>3</sub>NH<sub>2</sub>, whose PA exceeds again that of CH<sub>3</sub>NHOH by ca. 10 kcal mol<sup>-1</sup>. The effects of replacing one of the H atoms of NH<sub>3</sub> by the OCH<sub>3</sub> group are much smaller, less than 1 kcal mol<sup>-1</sup> from the comparison of the PA of NH<sub>3</sub> with that of H<sub>2</sub>NOCH<sub>3</sub>. The effects of the OH and the OCH<sub>3</sub> substituents on the basicity of N, deduced from experimentally measured PA values, are in line with expectations based on their inductive effect and with previous theoretical analyses.<sup>2</sup> The effect of the NH<sub>2</sub> and CH<sub>3</sub>NH substituents on the PA of the O atom can



1, Cs

2, Cs

Figure 4. Geometries of the neutral species and of isomeric  $(H_2NOH)H^+$  ions computed at the MP2(FU)/6+31G\* level of theory.



Figure 5. Geometries of the isomeric  $[(H_2NOH)CH_3]^+$  ions computed at the MP2(FU)/6-31G\* level of theory.

also be estimated by comparing the experimental PA of water with the computed PAs of the O atom of  $H_2NOH$  and  $CH_3$ -

NHOH. Substitution of one H atom of  $H_2O$  with  $NH_2$  appears to cause only a slight (ca. 1 kcal  $mol^{-1}$ ) increase, whereas, as

TABLE 3: MP4/6-311G\*\* Absolute Energies (hartree molecule<sup>-1</sup>) and Corrections (mhartree molecule<sup>-1</sup>) for the Evaluation of the G1 Energies of the Species of Interest

species	MP4/6-311G**	$\Delta E(+)$	$\Delta E(2df)$	$\Delta E(QCI)$	$\Delta E(\text{HLC})$	$\Delta E(\text{ZPE})$	G1(0K)	GI(298K) <sup>a</sup>
1	-131.776 94	-4.24	-65.17	-0.32	-42.98	55.41	-131.834 24	-131.830 97
2	-131.734 87	-3.49	-63.91	-0.52	-42.98	53.41	-131.792 36	-131.788 82
3a	-171.000 80	-4.90	-84.69	-0.48	-61.40	84.84	-171.067 43	-171.063 26
4a	-170.953 12	-4.92	-84.62	-0.55	-61.40	83.22	-171.021 39	-171.016 87
3b	-170.952 55	-4.76	-84.54	-0.82	-61.40	82.18	-171.021 89	-171.017 36
4b	-170.985 62	-5.12	-87.18	-0.53	-61.40	84.86	-171.054 99	-171.050 68
TS	-170.882 75	-7.06	-85.70	-2.12	-61.40	78.75	-170.960 28	-170.955 52
$CH_3^+$	39.379 70	-0.13	-13.87	-1.37	-18.42	32.50	-39.380 99	-39.378 14
NH <sub>2</sub> OH	-131.446 28	-11.42	-67.93	+0.04	-42.98	40.94	-131.527 63	-131.524 43
CH <sub>3</sub> NHOH	-170.653 82	-11.45	-88.15	-0.10	-61.40	70.19	-170.744 73	-170.740 63
CH <sub>3</sub> ONH <sub>2</sub>	-170.644 80	-10.99	-90.30	-0.07	-61.40	70.10	-170.737 46	-170.732 70

<sup>a</sup> Thermally corrected for rotational, translational and vibrational contributions.



Figure 6. Energy profile of the  $(H_2NOH)CH_3^+$  system from G1 calculations (0 K).

could be expected, the CH<sub>3</sub>NH substituent has a larger effect, enhancing the PA of the O atom by some 9 kcal  $mol^{-1}$ .

From the experimental PA of CH<sub>3</sub>NHOH and its known heat of formation, one can calculate  $\Delta H_f^{\circ}(3)$  and hence the exothermicity of the reaction

$$CH_3^+ + H_2 NOH \rightarrow 3 \tag{7}$$

that corresponds to the MCA of the N atom of H<sub>2</sub>NOH and amounts to  $102.7 \pm 4$  kcal mol<sup>-1</sup>, in excellent agreement with the 101.4 kcal mol<sup>-1</sup> value computed at the G1 level of theory. The MCA of the O atom of H<sub>2</sub>NOH is not amenable to experimental measurement. Nevertheless, it can be roughly estimated from the theoretically computed PA of the O atom of H<sub>2</sub>NOCH<sub>3</sub>, the heat of formation of the latter, and the heat of formation of the CH<sub>3</sub><sup>+</sup> cation to be ca. 71 kcal mol<sup>-1.6</sup> The result points to the much lower nucleophilicity of the O than the N atom, consistent with the trend observed in their relative basicity.

A final point that deserves discussion is related to the evidence from MIKE and CAD spectrometry for the predominant, if not exclusive, presence of isomer **3** in the ionic populations from reaction 1. In principle, this could be rationalized by invoking either a strong bias for N alkylation of  $H_2NOH$  by  $(CH_3)_2Cl^+$ or removal of the initially formed isomer **4** by some secondary process during the relatively large time lag, ca.  $10^{-5}$  s, before structural assay.

As to the first alternative, we note that, on the basis of the computed MCA of the O atom and the experimental MCA of  $CH_3Cl$ ,<sup>9</sup> O methylation of hydroxylamine is energetically allowed, although N alkylation is characterized by a larger exothermicity. Thus, if a bias for N alkylation does exist, it

must be of a purely kinetic nature, reflecting a sizable activation energy for O alkylation, which is reasonable for a lowexothermicity process. As to the second alternative, intramolecular  $3 \rightarrow 4$  isomerization is unlikely, in view of the high barrier computed at the G1 level of theory (Figure 6). Intermolecular isomerization, involving CH<sub>3</sub><sup>+</sup> transfer from 4 to the N atom of H<sub>2</sub>NOH, present as a neutral in the CI ion source, is a conceivable route to 3. Perhaps, the most likely explanation for the depletion of 4 in the ionic populations from (1) can, however, be based on the occurrence of fast proton transfer to H<sub>2</sub>NOH in the CI ion source. It should be noted, in this connection, that the reaction

$$4 + H_2 \text{NOH} \rightarrow 1 + H_2 \text{NOCH}_3 \tag{8}$$

is exothermic, owing to the lower PA of the O atom of  $H_2$ -NOCH<sub>3</sub> than of the N atom of  $H_2$ NOH, whereas the analogous proton transfer from **3** would be endothermic by some 11 kcal mol<sup>-1</sup>. Thus, the selective depletion of isomer **4** could be accounted for by the occurrence of the exothermic, and presumably very fast,<sup>10</sup> deprotonation process (8).

Most relevant to the present discussion, all the above explanations of the experimentally observed predominance of the N-methylated product from (1) point to the higher stability of isomer 3, in agreement with the computational results.

## **Experimental Section**

**Materials.** H<sub>2</sub>NOH·HCl was obtained from Aldrich Chemical Co., with a stated purity of 99.999%. Hydroxylamine phosphate was obtained from the hydrochloride upon treatment with a Na<sub>3</sub>PO<sub>4</sub> solution. Gaseous hydroxylamine was generated by decomposition of the phosphate at 90 °C under vacuum in the inlet systems of the ZAB and the FT-ICR mass spectrometers. *O*-Methylhydroxylamine and *N*-methylhydroxylamine were generated directly from their hydrochlorides from Aldrich Chemical Co. CH<sub>4</sub> and CH<sub>3</sub>Cl were obtained from Matheson Gas Products Inc. with a stated purity in excess of 99.95%.

Mass Spectrometric Measurements. CI, MIKE, and CID spectra were recorded using a double-focusing ZAB-2F mass spectrometer from VG Micromass Ltd. Hydroxylamine phosphate was introduced into the CI ion source using a specially built direct-insertion probe cooled and thermostated at a temperature of -40 °C. When the probe was inserted, its tip extended into the source, whose temperature was usually 160 °C, or above, and the solid gradually reached the decomposition temperature, generating gaseous hydroxylamine directly in the source.

Typical operating conditions were as follows: source temperature, 160 °C; repeller voltage, 0 V; emission current, 0.5-1

mA; accelerating voltage, 8 kV. The MIKE and CID spectra represent the sum of at least 40 scans acquired with an energy resolution of 4000 fwhm. Helium, used as the collision gas to record CID spectra, was admitted into the cell, adjusting the pressure to the lowest value required to achieve a spectrum with a good signal-to-noise ratio; typically, the main beam intensity was reduced to 30% of its original value. The ICR measurements were carried out using a Bruker Spectrospin Apex TM 47 spectrometer, equipped with an external CI ion source and a XMASS TM data system. Separate inlets were used to introduce the O- and N-methylhydroxylamine, at a total pressure of  $2.3 \times 10^{-8}$  Torr. Due to the facile decomposition of free NH<sub>2</sub>OH in the absence of an effective cooling system, its phosphate salt was introduced into the external source, and the protonated ion formed there was transferred into the resonance cell and allowed to react with different bases, as described in the text.

Computational Details. Ab initio quantum-mechanical calculations were performed by using an IBM RISC/6000 version of the GAUSSIAN 92 program package.<sup>11</sup> The standard 6-31G\*\*, 6-311+G\*\*, and 6-311G\*\* (2df)<sup>12</sup> basis sets were used throughout. Geometry optimizations were performed in the full space of the coordinates by analytical gradient-based techniques.<sup>13</sup> To this end, the 6-31G\* basis set was employed in the framework of the second-order Møller-Plesset pertubation theory (MP2).<sup>14</sup> The MP2 theory was used with full electron correlation (FU). The geometries obtained in this way are denoted by MP2(FU)/6-31G\*. The MP2(FU)/ 6-31G\* vibrational frequencies were computed for all of the investigated species in order to characterize them as true minima, a transition structure, or higher order saddle points on the corresponding potential energy hypersurfaces, and the zero-point vibrational energies (ZPVE) of the various species were taken into account in this way. The G1 procedure<sup>15</sup> was employed to obtain the total energies of the investigated species.

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**Supplementary Material Available:** A table listing the absolute energies of the species of interest (1 page). Ordering information is given on any current masthead page.

#### **References and Notes**

(1) Del Bene, J. E.; Frisch, M. J.; Raghavachari, K.; Pople, J. A. J. Phys. Chem. 1982, 86, 1529.

(2) Johansson, A.; Kollman, P. A.; Liebman, J. F.; Rothenberg, S. J. Am. Chem. Soc. 1974, 96, 3750.

(3) Lascola, R.; Andrews, L. J. Am. Chem. Soc. 1987, 109, 4765.

(4) Brown, R. E.; Zhang., Q.; Bartlett, R. J. J. Am. Chem. Soc. 1991, 113, 5248.

(5) Cotton, F. A.; Wilkinson, G. Advanced Inorganic Chemistry; Wiley: New York, 1980; p 422.

(6) For a discussion of the experimental approaches to PA measurement, see: Lias, S. G.; Bartmess, J. E.; Liebman J. F.; Holmes, J. L.; Levin, R. D.; Mallard, W. G. J. Phys. Chem. Ref. Data **1988**, 17, Suppl. 1. Except when noted otherwise, the compilation is the source of the thermochemical data used in this work.

(7) Szulejko, J. E.; Mc Mahon, T. B. J. Am. Chem. Soc. 1993, 115, 7839.

(8) (a) Majumdar, T. K.; Clairet, F.; Tabet, J. C.; Cooks R. G. J. Am. Chem. Soc. 1992, 114, 2897. (b) Cooks, R. G.; Kruger, T. L. J. Am. Chem. Soc. 1977, 99, 1279. (c) McLuckey, S. A.; Cameron, D.; Cooks, R. G. J. Am. Chem. Soc. 1981, 103, 1313. (d) Wright, L. G.; Mc Luckey, S. A.; Cooks, R. G.; Wood, K. V. Int. J. Mass Spectrom. Ion Processes 1982, 42, 115.

(9) Mc Mahon, T. B.; Heimis, T.; Nicol, G.; Hovey, J. R.; Kebarle, P. J. Am. Chem. Soc. 1988, 110, 7591. See also ref 6.

(10) Exothermic proton-transfer reactions involving n-type basic centers are usually very fast in the gas phase, occurring at, or nearly to, collision rate, unless hindered by steric factors, which is not the case of the bases of interest. Cf: Su, T.; Bowers, M. T. *Gas Phase Ion Chemistry*; Bowers, M. T., Ed.; Academic Press: New York, 1979; Vol 1, p 184.

(11) Frisch, M. J.; Trucks, G. W.; Head-Gordon, M.; Gill, P. M. W.; Wong, M. W.; Foresman, J. B.; Johnson, B. G.; Schlegel, H. B.; Robb, M. A.; Replogle, E. S.; Gomperts, R.; Andres, J. L.; Raghavachari, K.; Binkley, J. S.; Gonzalez, C.; Martin, R. L.; Fox, D. J.; Defrees, D. J.; Baker, J.; Stewart, J. J. P.; Pople, J. A. *Gaussian 92*, Revision A; Gaussian, Inc.: Pittsburgh, PA, 1992.

(12) (a) Hariharan, R. C.; Pople, J. A. Chem. Phys. Lett. 1972, 66, 217.
(b) Krishnan, R.; Binkley, J. S.; Seeger, R.; Pople, J. A. Chem. Phys. Lett.
1980, 72, 4244. (c) Frisch, M. J.; Pople, J. A.; Binkley, J. S. J. Chem. Phys., 1984, 80, 3265.

(13) Schlegel, H. B. J. Comput. Chem. 1982, 3, 214.

(14) Møller, C.; Plesset, M. S. Phys. Rev. 1934, 46, 618.

(15) Pople, J. A.; Head-Gordon, M.; Fox, D. J.; Raghavachari, K.; Curtiss, L. A. J. Chem. Phys. **1989**, 90, 5622.

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