Oxygen-17 Nuclear Magnetic Resonance Studies of the Structures of Benzohydroxamic Acids and Benzohydroxamate Ions in Solution[1]

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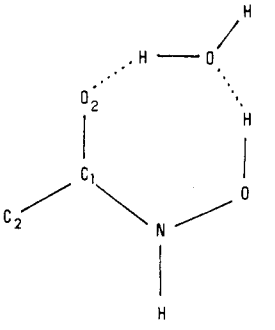
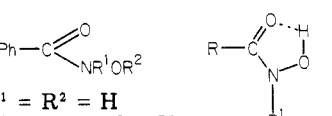
The ^{17}O NMR chemical shifts of the carbonyl oxygens have been determined for benzohydroxamic acid (1) and its *N*-methyl (2), *O*-methyl (3), and *N,O*-dimethyl (4) derivatives in dioxane, benzene, and methanol and as functions of pH in the last solvent. The observed chemical shift values (330–350 ppm downfield in dioxane from external H_2O) are in the range characteristic of benzamides, supporting the amide structure A. Upfield shifts of ca. 31 and 57 ppm were observed for the *N*-methyl (2 and 4) and NH compounds (1 and 3), respectively, in methanol solutions. Stronger hydrogen bonding with the solvent molecules in the NH compounds was suggested. From the ^{17}O chemical shift titration curves of these compounds, the pK_a values were obtained as 10.1, 9.8, and 10.8 for 1–3, respectively. On deprotonation, the carbonyl oxygen of 1 suffers an upfield shift of 72 ppm which corresponds better with that of 3 (83 ppm), namely, NH deprotonation. A smaller but significant upfield shift for 2 indicated unexpectedly large charge delocalization on OH dissociation. The pH dependence of ^{13}C chemical shifts due to the carbonyl and aromatic ring carbons in methanol was less conspicuous. The NH compounds 1 and 3 behaved similarly to each other, supporting the conclusions obtained from ^{17}O NMR. The NH deprotonation in 1 and dipole stabilization of the terminal O anion were supported by the ab initio MO theoretical calculations.

Hydroxamic acids have shown many interesting facets of chemistry since first reported more than a century ago.[3] Lossen found at the evolutionary stage of the chemistry of hydroxamic acids a rearrangement reaction of their *O*-acyl derivatives which bore his name[4] and found synthetic usefulness in converting carboxylic esters through hydroxamic acids and isocyanates into the corresponding amines with one less carbon atom. Many hydroxamic acids were found in the meantime to be biologically active,[5] present in fungal metabolites,[6] and useful as a variety of drugs.[7] Both hydroxamic acids and their N-substituted derivatives serve as bidentate ligands toward many metal ions such as Fe(III) and Cu(II). The resultant complexes are highly colored and therefore are useful in colorimetric analyses of metal ions.[8] One of the elegant applications in this field is the recent use of chiral hydroxamic acids as ligands for a vanadium catalyst to be used in asymmetric epoxidation of allylic alcohols.[9]

In spite of these interesting properties, hydroxamic acids remain one of the less well-characterized classes of organic compounds. A major difficulty lies in assigning a correct structure which can be represented by one of a number of tautomeric structures, A–C. Possibilities of geometrical isomerism and internal hydrogen bonding add considerably to the complexity. The controversial situations have been mostly lifted by application of modern physicochemical methods to structural study. Thus an X-ray diffraction study shows that acetohydroxamic acid hemihydrate in the solid state may be represented by structures A and C.[10] Atoms C_1, C_2, N, and O_2 define a molecular plane with the OH oxygen 0.56 Å away from the plane. The C–N bond length of 1.33 Å can be associated with the bond order of about 1.5.



Many IR spectra of hydroxamic acids are reported.[11] The most informative difference between structures A and B would be the presence of the C=O and C=N vibration bands, respectively. The difference in frequencies between $\nu_{C=N}$ in benzoimidates (1639 cm^{-1}, neat) and the amide I band of benzohydroxamic acids (1640 cm^{-1}) is, however, too small to settle the diagnosis. In dry dioxane, benzohydroxamic acids 1–3 show absorptions at 1640, 1670, and 1694 cm^{-1}, respectively. Exner and Kakáč[11d] have interpreted the high absorption frequency for 3 as evidence for



1, $R^1 = R^2 = H$
2, $R^1 = CH_3$; $R^2 = H$
3, $R^1 = H$; $R^2 = CH_3$
4, $R^1 = R^2 = CH_3$

A′

(1) Part 10 of the series titled "^{17}O Nuclear Magnetic Resonance Studies". Part 9: Onaka, S.; Sugawara, T.; Kawada, Y.; Iwamura, H. *J. Chem. Soc., Dalton Trans.* **1982**, 257. Also Part 3 of "Chemistry of Hydroxamic Acids". Part 2: Lipczyńska-Kochany, E. *Wiad. Chem.*, in press.

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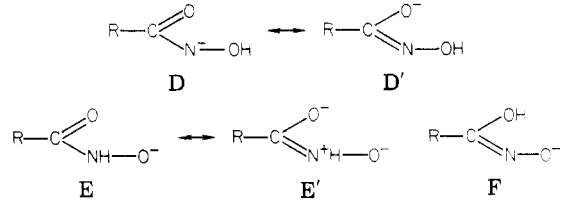
free amide and therefore the lower frequency amide I bands as representing the intramolecular hydrogen bond as in A'.

Whereas UV absorptions of arylhydroxamic acids are similar to those of their N-substituted derivatives in polar solvents, the former behave differently from those of ethyl *syn*-benzohydroximate.[11d,12] The dipole moments (4.3–4.5 D) of arylhydroxamic acids in benzene and dioxane solutions are larger than those of the corresponding amides and, therefore, are explained by the *Z* configuration of structure A.[13]

Hydroxamate ions are particularly effective for a nucleophilic attack at the phosphorus atom of phosphonic and phosphoric anhydrides. It is the oxygen atom attached to the nitrogen which usually gets bonded to the electrophilic center.[14] However, the observation does not afford a clue for the thermodynamically favorable structure of the anions. On the basis of the pK_a values and rate constants for the reaction of isopropyl methylphosphonofluoridate with 1–3, Steinberg and Swidler concluded the benzohydroxamate to be present in aqueous solution in forms D and E in approximately equal concentration. However, a possible existence of form F could not be ruled out.[14]



Both hydroxamic acids and their *N*- and *O*-methyl derivatives are nearly equally stronger acids (pK_a of 8–10) than the corresponding amides.[8] It remains an unsolved puzzle that *N*-methyl derivatives appear to be strongest acids among them. The Hammett plots of the ionization constants of a series of para-substituted benzohydroxamic acids give a ρ value close to unity, supporting the NH dissociation.[15]

As opposed to the anion of **2** which exhibits the ^1L_a band shifted hypsochromically relative to that of **2**, a bathochromic shift is observed on going from **1** and **3** to the corresponding anions. The observation led Plapinger[12] to the conclusion that the anion of **1** contained contributions of at least two and possibly even three forms, i.e., D, E, and/or F. An IR study of the salt of deuterated **1** in the solid state and in dioxane showed the presence of O–D vibrations, suggesting structure D.[11e] Steinberg and Swidler favored structures E and D ↔ D' in approximately equal concentration in aqueous solution.[14c]

NMR spectroscopy has been proven to be one of the most useful techniques in determining molecular structures in solution. Strangely enough only few ^1H NMR studies are reported for hydroxamic acids.[16] They are mainly concerned with hindered rotation around the C(O)–N bond with partial double bond character in N,O-disubstituted compounds. It may be the case that ^1H NMR spectroscopy is not a good strategy in these systems as many exchanging sites are involved, especially in protic solvents.

As a summary of the literature survey, we note that, whereas hydroxamic acids in solution may have structure A' (internal hydrogen bonding in the *Z* configuration), the structure of hydroxamate anions in solution (D–F) still remains contentious. We have therefore undertaken ^{17}O and ^{13}C NMR measurements of benzohydroxamic acid (**1**) and its *N*- and *O*-methyl and *N*,*O*-dimethyl derivatives (**2–4**, respectively) in solution. Samples specifically enriched with ^{17}O at the structurally more informative carbonyl oxygen were employed for the former measurement. We report in this paper solvent effects and pH dependence in methanol of the ^{17}O and ^{13}C chemical shifts.

Table I. ^{17}O NMR Chemical Shift Data for 1–4 in Different Solvents

	shift, ppm			
compd	dioxane	benzene	methanol	alkaline methanol[a]
1	333	*b*	277	204.5
2	330	303	298.5	263.5
3	341	344	283.5	201
4	347	351	316	317

[a] pH >12. [b] Solubility was too low to get data.

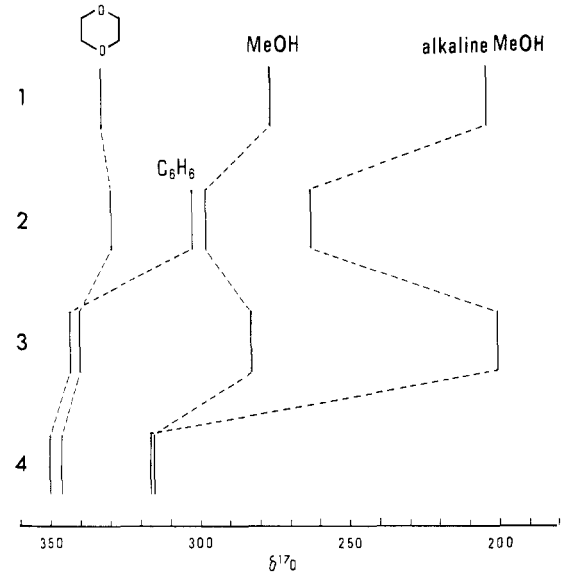


Figure 1. Schematic representation of ^{17}O chemical shifts due to the carbonyl group of 1–4 in different solvents and under anion formation.

Results and Discussion

^{17}O NMR for Benzohydroxamic Acids. ^{17}O NMR spectra due to the carbonyl groups of 1–4 were taken in anhydrous benzene, dioxane, and methanol. The low solubility of **1** in benzene did not allow us to obtain a ^{17}O resonance signal in this solvent. The results are given in Table I and illustrated in Figure 1.

The ^{17}O NMR signals of the carbonyl oxygens in benzene and dioxane appear at δ 300–350 (in parts per million downfield from external H_2O) which is the region characteristic of the amide carbonyl resonances, suggesting that **1–4** are all present predominantly in the structure A of hydroxamic acids. More careful examination of the effects of the methyl substitution and solvents reveals a number

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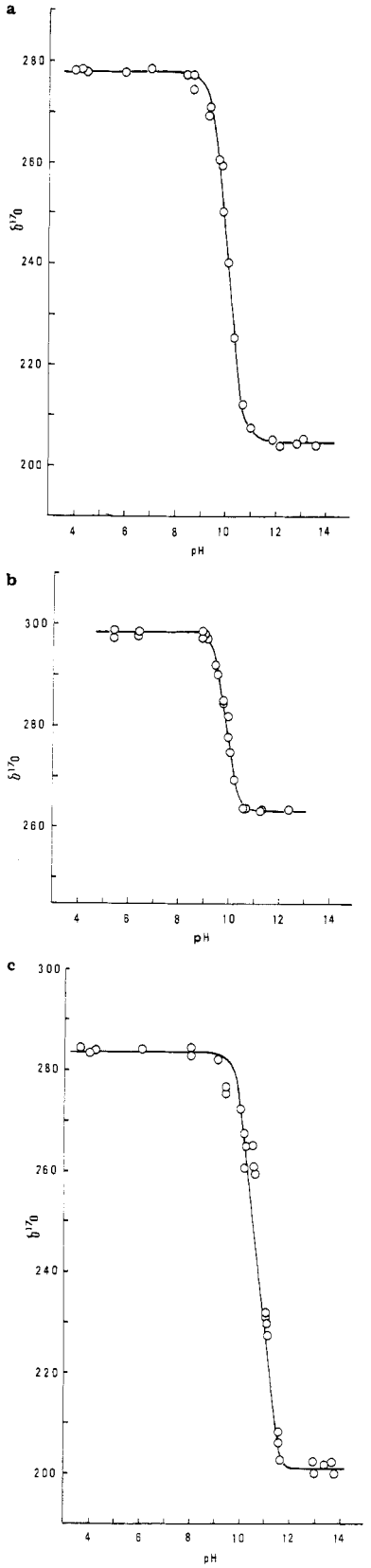
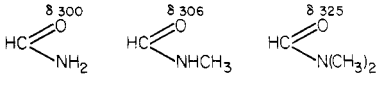
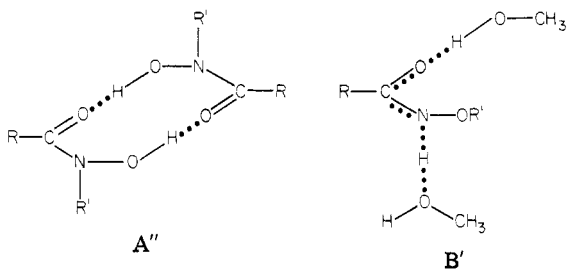


Figure 2. ^{17}O chemical shift vs. pH curves for the methanol solutions of (a) benzohydroxamic [C=^{17}O]acid (1), (b) *N*-methylbenzohydroxamic [C=^{17}O]acid (2) and (c) *O*-methylbenzohydroxamic [C=^{17}O]acid (3).

of pertinent points. It is noted in a series of formamides (see below) that introduction of an *N*-methyl group leads



to a downfield shift of the carbonyl oxygens.[17] A similar trend is found in benzohydroxamic acids too. Thus 4 shows the ^{17}O signal of the carbonyl group at lower field than that of 3 and 1 both in dioxane and benzene. However, significant upfield shifts are noted for 2, especially in benzene, and could be ascribed to intramolecular hydrogen bonding as in A′ or to dimer formation A″. Hydrogen bonding effects on oxygen chemical shifts are well-established. The carbonyl oxygen of acetone, for example, experiences up to a ca. 52-ppm upfield shift in water relative to pure acetone. The upfield shift has been attributed to the increased contribution of the polar valence bond resonance structure $>C^{+}-O^{-}$.[18] A similar effect appears to be operative in internal hydrogen bonding: δ 507 of salicylaldehyde vs. 569 of benzaldehyde.[19] In dioxane the observed upfield shifts for 1 and 2 relative to the shifts of 3 and 4 are not very dramatic, suggesting the breaking of the internal hydrogen bonding to some extent in this proton-accepting solvent. Methanol solvent causes an upfield shift too. The shift values of 31 and 35 ppm for 4 on changing from dioxane and benzene, respectively, to methanol are considered to be due purely to the hydrogen bonding effect by solvation. Taking these values as a reference for comparison, we first note that a change in chemical shifts for 2 on going from dioxane to methanol is comparable to that of 4. The chemical shift values are not very different in benzene and methanol solutions. These observations are again in line with structure A′ (or A″) in benzene and almost no internal hydrogen bonding in dioxane. Solvation of 2 with methanol, if present, may not be able to perturb the carbonyl oxygen any further in A′ (or A″). Alternatively, internal hydrogen bonding might have been replaced by external MeOH···O=C bonding to effect the polarization of the carbonyl group as much as in 4. Second, more pronounced upfield shifts (>50 ppm) are noted for 1 and 3 on going from dioxane (and also benzene for 3) to methanol. A mechanism for stronger solvation at the carbonyl oxygen has to be taken into account. As these two compounds carry a free NH group, a slight contribution of structures B and/or C may provide an explanation. In other words, multiple hydrogen bonding in which one methanol molecule is serving as a hydrogen donor to the carbonyl oxygen and a second methanol molecule as a hydrogen acceptor of the NH group (B′) is a possibility. The combined push–pull effect of solvation would increase negative charge at the carbonyl oxygen such that a large upfield shift may result.[20]



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(20) Due to the limited sensitivity of the ^{17}O NMR measurement, a dilution study was not carried out to differentiate between A′ and A″. The association questions could be answered by IR dilution studies and/or by vapor-phase osmometry (suggestions by a referee) independently from this study.

Table II. ^{13}C NMR Chemical Shift Data for 1-4 in Methanol in the Absence and Presence of Added Alkali

		shift, ppm				
			aromatic ring carbons			
compd	solvent	C=O	ipso	others	NCH_3	OCH_3
1	methanol	168.3	133.5	132.7, 129.6, 128.1		
	methanol + methoxide[a]	166.6	137.0	130.4, 129.1, 127.6		
2	methanol	172.1	135.4	131.3, 129.1, 128.9	38.1	
	methanol + methoxide	165.9	139.1	130.2, 129.6, 128.3	42.5	
3	methanol	167.7	133.0	132.8, 129.4, 128.1		64.1
	methanol + methoxide	167.8	139.5	129.4, 128.6, 128.1		60.4
4	methanol	171.5	135.3	131.7, 129.1, 128.9	34.1	61.4

[a] pH >12.

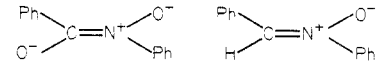
^{17}O NMR for Benzohydroxamates. The pH chemical shift titration curves obtained for **1-3** in methanol are reproduced in Figure 2. A significant upfield shift was always observed on raising pH of the methanol solutions. It goes without saying that chemical shift values of **4** do not change at all even at very high pH.

At this point a doubt might be raised about the probability of hydrolysis of the samples at high pH. This was excluded by the observation that chemical shifts followed the same plots as in Figure 2 when the pH of the solutions was decreased after running a series of measurements at high pH. ^1H NMR and HPLC showed no hydrolysis product after the ^{17}O NMR measurements. We also point out that carboxylic acids generally lead to a downfield shift on raising of the pH of the solution.[18c,21] In our hands, benzoic acid (δ 243 at pH 3.5) showed a 19-ppm downfield shift on forming benzoate anion (δ 262 at pH 12.9) in methanol.

The pK_a value defined as the pH of the solution where an acid and the conjugate base are in equal concentration was obtained as 10.1, 9.8, and 10.8 for **1-3**, respectively, with the aid of the Henderson-Hasselbach equation.[22] A number of pK_a values of benzohydroxamic acids are reported.[8] The data in aqueous solution are scattered, but typical pK_a values are 8.80, 8.59 and 8.88 for **1-3**, respectively, at 30 °C.[14c] Our data in methanol are in the same order but deviated to the higher pK_a values by 1.2-1.9. It is generally accepted that dissociation of acids is suppressed by 1-2 pK_a units in methanol as compared to aqueous solutions.[23]

The similar chemical shift values between the anions of **1** (δ 205) and **3** (δ 201) clearly show that the anion of **1** has the NH deprotonated structure D. The magnitudes of the upfield shifts, 72 and 83 ppm for **1** and **3**, respectively, suggest a considerable charge density transfer from the nitrogen atom to the carbonyl oxygen, namely, a great contribution of structure D′ in the hydroxamate ions. What does the ca. 10% smaller upfield shift of **1** relative to **3** mean? As OH deprotonation of **2** leads to an upfield shift of 35 ppm, we could argue algebraically that the anion of **1** might have a tautomeric structure with 20% OH and 80% NH deprotonations. We are inclined to take an alternative explanation; the difference may be due not to the contribution of OH dissociation, namely, structure E, but to an indication of the slightly different substituent I effect of OH (σ^* 0.555) vs. OCH_3 (σ^* 0.520).[24] As the hydroxyl is more electronegative than the methoxyl, structure D′ would be slightly less favored relative to D in **1**.

An upfield shift as much as 35 ppm obtained for **2** was a rather unexpected one. Deprotonation of OH is obvious here. Therefore, unexpectedly large charge delocalization must be taking place. This may be appropriately represented by resonance structure E′. An independent support for the conclusion is provided by the large bathochromic shift from λ_{max} 270 to 310 nm observed for *N*-phenylbenzohydroxamate ions.[25] Deprotonation from the OH group is obvious, but structure E alone cannot explain the observed shift. A major contribution of structure E′ in this anion is suggested by close similarity of its absorption to that of *C,N*-diphenylnitrone[26] (see below).



Once polarization of the carbonyl group is induced inherently in the molecule, solvation with methanol will also be strengthened to effect further upfield shifts. A precedent for a similar long-range effect of the electric charge on the carbonyl ^{17}O chemical shift can be found in glycylglycine.[27] Deprotonation of the carboxyl and amino ends of the dipeptide is reported to induce upfield shifts of the amide carbonyl oxygen by 6 and 16 ppm, respectively. On going from the cationic to anionic states, the amide C-N double bond character increases and a transfer of electron density from the nitrogen to the oxygen should occur (see below).

$$NH_2CH_2C(O)NHCH_2CO_2H$$

^{13}C NMR for Benzohydroxamic Acids. ^{13}C NMR spectra were taken in methanol-d_4, and the chemical shift values in the absence and presence of sodium methoxide are collected in Table II. The aromatic and carbonyl carbon signals are almost superimposable to each other in *N*-methyl compounds **2** and **4**. Taking these data as a reference for comparison, we note the following trends.

Both the carbonyl and quaternary ring carbons appear to experience a slight but definite upfield shift in **1** and **3** with free NH. In the previous section we noted that ^{17}O chemical shifts of these two compounds were conspicuously upfield shifted in methanol. If the effect of hydrogen bonding of methanol to the carbonyl oxygen and the resultant polarization of the carbonyl group in the sense $>C^+-O^-$ are operative in determining ^{13}C chemical shifts, the carbon signals under consideration should have undergone downfield shifts. Actually downfield shifts of 2.5-4 ppm are reported for typical ketones.[28] The values are

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slightly smaller (0.5–2 ppm) for ester carbonyls on hydrogen bonding in methanol solution.[28a] The observed upfield shifts in 1 and 3 are opposite the general trend. Within the limits of the charge density control of ^{13}C chemical shifts, the upfield shifts suggest the neutralization of the plus charge at the carbonyl carbon in 1 and 3. The electron-donating ability of the amide nitrogen to the carbonyl moiety must be facilitated by structure B′ previously proposed. Both *N*- and *O*-methyl groups in 4 are more shielded than the corresponding methyl groups in 2 and 3. The magnitude of the shieldings are explicable in terms of the steric γ effect.[29]

^{13}C NMR for Benzohydroxamates. Addition of sodium methoxide to provide anions affected the ^{13}C chemical shifts significantly. An upfield shift of the carbonyl carbon by 6.2 ppm is accompanied by downfield shifts of the quaternary ring and *N*-methyl carbons in 2. As seen more conspicuously in the ^{17}O chemical shift, charge delocalization from the terminal oxygen to the carbonyl group is indicated. Canonical structure E′ or a change in hybridization at the nitrogen may be responsible for the lowfield shift of the *N*-methyl carbon. Changes in ^{13}C chemical shifts observed in 1 and 3 are different from those of 2. The carbonyl carbon of 1 experiences only a slight upfield shift, and that of 3 is very slightly downfield shifted. The ^{13}C resonances of the carboxyl and the neighboring carbon atoms shift several parts per million downfield upon ionization to the carboxylate.[30] The observed trend in 3 is in accord with the carboxylates, suggesting structures D ↔ D′. The magnitude of the downfield shift of the carbonyl carbon is much smaller in 3 (0.1 ppm) than in carboxylic acids (≥20 ppm). An upfield shift of the carbonyl carbon due to reduced electronegativity in the N^-OH unit may be considered to be suppressed by a similar effect in 1.

Wherever deprotonation takes place in hydroxamic acids, the hydroxamate group will be substantially less electronegative than the undissociated acids. Downfield shifts are, however, always observed at the ipso carbon of the benzene ring. Thus the limit of simple charge density arguments is apparent. Perhaps paramagnetic screening associated with the effective excitation energy of the 2p electrons must be dominating the shielding of this second-row nucleus.[31]

Ab Initio MO Theoretical Considerations

Ab initio SCF MO calculations in the 3-21G level have been carried out on formohydroxamic acid.[32] The results are summarized in Figure 3. The intramolecular hydrogen bonding present as in A′ with the H···O distance of about 2.09 Å is a contributing factor in stabilizing this form by ca. 7.0 kcal/mol relative to the nonhydrogen bonding conformation.[32] As is generally the case for hydrogen bonded systems, the stabilization comes mainly from the charge-transfer effect (from the carbonyl group to the hydroxyl), but the charge distribution is mostly governed by the polarization term which tends to increase the

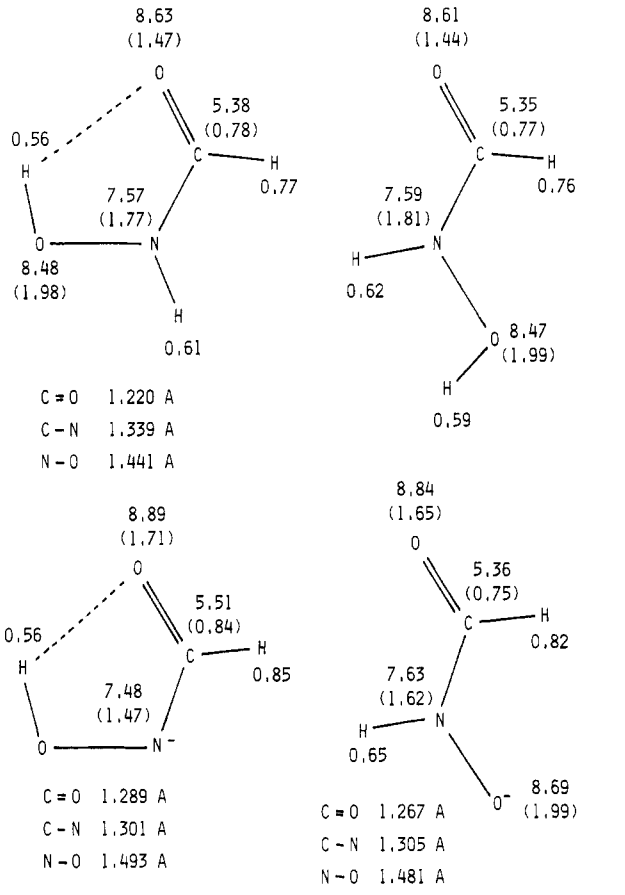
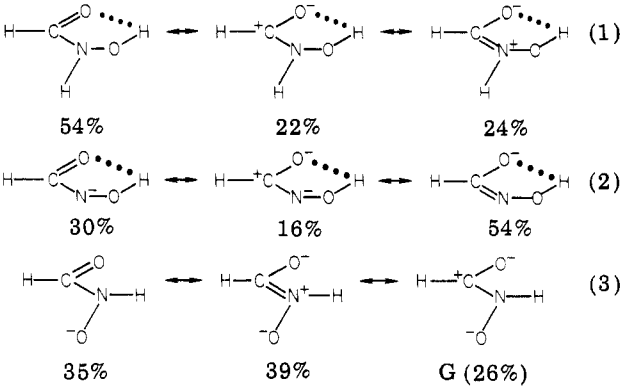


Figure 3. Electron density (π-electron density) distributions and relevant bond length data in formohydroxamic acid and its anions. The structures are fully optimized except for the *E* conformation of the free acid for which the bond lengths and angles found for the *Z* conformation are assumed with the C–N bond rotated 180°.

electron density at the carbonyl oxygen. The π-electron density distribution in the A′ form obtained by population analyses of the MO's can be approximated by contribution of the canonical structures as in eq 1.



N-Anion D is predicted to be more stable than O-anion E by ca. 0.7 pK_a unit. Internal hydrogen bonding is still present. Resonance structure D is now contributing only to an extent of 30% (eq 2).[32]

A negative charge is extensively delocalized over the entire hydroxamate framework in O-anion E. A high contribution of resonance structures E′ (39%) and G (26%) (eq 3) is derived from unexpectedly high π-electron density (1.65) at the carbonyl oxygen. An observed upfield shift as large as 35 ppm is thus consistent with theory. The electronic structure of the O-anion is highly reminiscent of the dipole-stabilized α-heteroatom carbanion of esters and amides.[33] Our results are consistent with their the-

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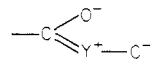
(32) The details will be published later by K. Morokuma, E. Lipczyńska-Kochany, and H. Iwamura. The 3-21G basis set was augmented by addition of diffuse p functions on all nonhydrogen atoms for the computation of the anions. For the necessity of this procedure for a reliable estimation of the anion stability, see: Chandrasekhar, J..; Andrade, J. G.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 5609.

oretically predicted preference of the anti conformation.[34] Resonance structure H appears not to be important there.



H (Y = O, NR)

Both theory and experiment agree with respect to enhancement of resonance structure E′ and G in *O*-hydroxamate ions. Higher electron density and possibly a lower ionization potential of the oxygen anion attached to the nitrogen as compared to those of the carbanion may be responsible for the discrepancy.

Our previous study has shown that ^{17}O chemical shifts are empirically proportional to the π-electron density at the oxygen (a line with a slope of ca. 2000 ppm/π electron).[35] On the basis of the linear relationship, the theoretically predicted increase in the π-electron densities at the carbonyl oxygen by 0.24 and 0.18 for the N- and O-anions, respectively, would dictate the upfield shifts of the ^{17}O resonances by 480 and 360 ppm which are an order of magnitude larger than the observed upfield shifts (72, 83, and 35 ppm for **1**–**3**, respectively). This discrepancy may be attributed firstly to the effect of the phenyl group (attached to the carbonyl in the experiment but not in the theoretical treatment) which would neutralize the charge migration. Second, ion pairing of the sodium cation with the N–O anionic center could possibly be attenuating the flow of negative charge toward the carbonyl oxygen.

The potential energy hypersurfaces for the reaction of H_2O and OH^- with fulminic acid have been investigated by ab initio calculations.[36] Stable products in these reactions are shown to be the *Z* configuration of hydroxyformaldoxime, corresponding to our structure B, and of oximate F. Therefore, as long as isolated molecules without any solvation are concerned, these structures appear to sit in the local minimum of the potential energy surfaces and have to be taken seriously.

The reason NH deprotonation takes place in **1** and yet *N*-methyl derivative **2** is a stronger acid than **1** and **3** still remains to be solved. The present study has revealed the occurrence of unexpectedly extensive charge delocalization in the anion of **2** which may be expressed in terms of canonical structure E′. Thus structure E′ should be less stable than structure D ↔ D′ when a hydrogen atom is attached to nitrogen. The situation would be reversed when a methyl group is introduced to the nitrogen center to neutralize the positive charge in E′. As methylamine (pK_a of $CH_3NH_3^+$ 10.68) is a stronger base than ammonia (pK_a of NH_4^+ is 9.25 at 25 °C) by 1.43 pK_a units,[37] the observed subtle difference (0.2 pK_a unit) between **1** and **2** is within the range of the above effect of methyl substitution.

Conclusions

In summary, comparison of the ^{17}O NMR chemical shifts of the carbonyl oxygens of benzohydroxamic acid (**1**) and its methyl derivatives **2**–**4** shows that **1** is represented by structure A in solution. Intramolecular OH···O=C hydrogen bonding in the *Z* configuration is important in nonpolar solvents. Polarization of the carbonyl group is induced by solvation in methanol. The effect is more pronounced for NH compounds **1** and **3** than for NCH_3 derivatives **2** and **4**. A large upfield shift (72 ppm) induced by deprotonation of **1** is mostly explained in terms of formation of N-anion D.

Experimental Section

Benzohydroxamic [C=^{17}O]Acids. Benzoyl chloride (3.8 g) was saponified in anhydrous dioxane with enriched sodium hydroxide-^{17}O which in turn was prepared in situ from sodium hydride (2 equiv in water) and 0.5 g of water-^{17}O (30 atom %, Prochem). Enriched benzoyl chloride was obtained by refluxing the enriched benzoic acid in excess thionyl chloride. The ^{17}O-enriched samples of **1**–**3** were prepared from benzoyl-^{17}O chloride and the corresponding hydroxylamine derivatives according to the standard methods in the literature.[11d,38]

Sample Solutions. For ^{17}O NMR measurements, 0.3–0.6 M solutions of the ^{17}O-enriched samples in dioxane, benzene, and methanol (all solvents were GR grade of Katayama Chemical Co. and Nakarai Chemicals, Ltd.) were employed. A ca. 10% solution of sodium methoxide in methanol was used for titration. Samples for ^{13}C NMR measurements were unenriched and dissolved in methanol-d_4 to make ca. 0.2 M solutions.

The pH values of the solution in methanol were determined on a Hitachi-Horiba Model F-7ss II pH meter with the aid of a Horiba Ag–AgCl electrode. A Taiyo thermostat unit was employed to maintain the measurements at 303 K. The electrode was calibrated with a phosphate (pH 7.00) and a borate (pH 9.00) buffer.

NMR Measurements. Fourier transform ^{17}O NMR measurements were made on a Varian FT-80A spectrometer operating at 10.782 MHz and externally locked on a deuterium oxide signal. Two-milliliter solutions in a 10-mm (o.d.) sample tube were employed at ambient temperatures of 30 ± 1 °C. Transients [(1–2.5) × 10^5] were accumulated with a 90° pulse and an acquisition time of 0.02 s. For an 8000-Hz spectral width, 323 data points were available in the time-domain spectra by keeping the Fourier number at 16 384. The signal-to-noise ratios were better than 15 for the enriched oxygen under these conditions. Chemical shifts were measured as frequency shifts from the synthesizer frequency (8.532 MHz) and are expressed in parts per million. A positive chemical shift denotes a resonance to a lower field than that of water oxygen which resonated at 10.783 17 MHz, and is considered to be accurate to ±0.5 ppm.

The proton wide-band decoupled ^{13}C NMR spectra were obtained on a JNM FX-100 (25.1 MHz) spectrometer with an internal deuterium lock. Two-milliliter solutions in methanol-d_4 in a 10-mm o.d. sample tube were used. Accumulation of pulse interferograms (pulse width of 6 μs, pulse interval of 1.00 s, and ca. 100 pulses) was followed by Fourier transformation (8 K). Chemical shifts are referenced to internal tetramethylsilane and are accurate to ±0.1 ppm.

Registry No. **1** (^{17}O-carbonyl), 83693-38-3; **2** (^{17}O-carbonyl), 83693-39-4; **3** (^{17}O-carbonyl), 83704-19-2; **4** (^{17}O-carbonyl), 83704-20-5; formohydroxamic acid, 4312-87-2.

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