The Search for Stable Nitrenium Ions: Protonation of Benzoquinone Monooximes in Superacids and the Study of Their Structure by Proton and Carbon-13 Nuclear Magnetic Resonance Spectroscopy[1]

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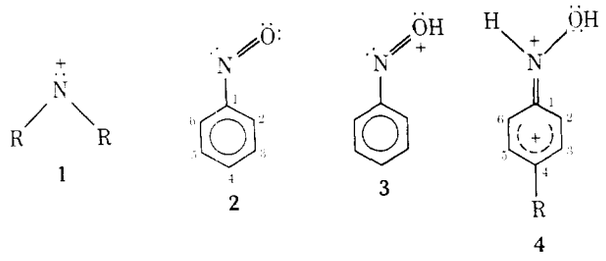
A series of substituted benzoquinone monooximes were protonated with HSO_3F–SbF_5 in SO_2 solution. ^1H NMR spectroscopy has shown that these precursors form diprotonated heteroatom species. Using ^{13}C NMR spectroscopy, the nature of the diprotonated cations was determined by a comparison of the chemical shift data with those of related model compounds. It was demonstrated that the dictations are of onium–benzenium ion nature, with the nitrenium ion form not contributing significantly to the overall structure. The γ-substituent effects observed for the dicationic species were studied in relation to the geometry of the substituent to the syn and anti ring carbons. A secondary γ-substituent effect was also observed in the dications. Both effects were empirically measured and shown to be constant and additive.

Gassman and co-workers suggested that nitrenium ions (1) are involved as intermediates in the reactions of *N*-hydroxy- and *N*-chloroaniline derivatives under neutral conditions.[2-5] Kinetic data and product analysis support the intermediacy of the nitrenium ions. However, in the recent papers of Okamoto and co-workers[6-8] on the strong acid-catalyzed reactions of nitrobenzene, *N*-hydroxyanilines, and dialkylaniline oxides with benzene, it was proposed that the intermediates are iminiumbenzenium dications (4) rather than nitrenium ions (3).



1 2 3 4

In the anodic oxidation of substituted diphenylamines by Serve,[9] it was possible to identify substituted diarylnitrenium ions under basic conditions and the doubly charged substituted N-protonated *N*-phenylanilenium ion under acidic conditions. The lifetime of these intermediates, however, was too short under the conditions employed, and it was thus not possible to examine the nature and structure of these nitrenium and protonated nitrenium ions.

In order to study the possibility of long-lived arylnitrenium ions, we have extended our continued study of cationic organic intermediates to the protonation of nitrosobenzenes (2) with "magic acid" in sulfur dioxide solution. ^1H NMR spectroscopy shows that diprotonated derivatives of **2** are observed as stable species (4). The nature of these species was determined by ^{13}C NMR spectroscopy. Geometrical isomers of the para-substituted derivatives of **4** were also identified from the ^{13}C NMR spectra. By using methyl groups to control the geometry, unequivocal peak assignments were possible for the isomers.

The latter part of our studies deals with the question of γ-substituent effects in these systems. A comparative study with selected model compounds allowed some qualitative conclusions to be made concerning the effects of γ substituents in the eclipsed conformations.

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Results

A series of para-substituted nitrosobenzenes were prepared and protonated with magic acid (1:1, HSO_3F–SbF_5) in SO_2 solution. The ^1H NMR chemical shift data, which are summarized in Table I, were assigned based on comparison between **5** and **6**. The absence of the highly deshielded absorption at δ 14.3 in **6** proved that this absorption in **5** is due to the protonated ketone function (4-OH) since protonated ketones absorb near $\delta_{^1H}$ ~14. The broadened absorption around $\delta_{^1H}$ 13 indicates a proton bonded to nitrogen. The remaining peak around $\delta_{^1H}$ 12 was assigned to that of the proton on the nitroso oxygen atom. In the ^1H NMR spectra, the chemical shifts of the ring protons of the protonated benzoquinone monooximes were usually complex and overlapped, so that specific assignments were generally not possible. In the substituted derivatives **10B, 11,** and **12A,** however, the methyl group simplified the spectra and assignments could be made unequivocally. All of the ^1H NMR spectral parameters of the benzoquinone monooximes in magic acid solution show them to be diprotonated species.

In order to obtain more information about the structure and nature of the diprotonated benzoquinone monooximes, their ^{13}C NMR spectra were also measured in the cases of **5A–16** (Table II). The assignments of the ^{13}C NMR chemical shifts given in Table II are based on the usual combination of proton-decoupled and -coupled NMR techniques and a comparison of methyl-substituted derivatives of **5** with related model compounds.

From the proton-decoupled and partially coupled ^{13}C NMR spectra, assignments for C_1 and C_4 were determined. A comparison between **16,** where C_1 is equivalent to C_4, and the other dications allowed C_1 and C_4 to be assigned unequivocally from $\delta_{^{13}C}$ 145.3–148.2 and 192.1–197.9, respectively. The assignments for C_1 and C_4 of **13A** and **14** are based on the additivity relationships generally observed for monosubstituted benzenes.

The complexity of spectral parameters for C_2, C_3, C_5, and C_6 made their ^{13}C chemical shift assignments difficult. For example, when a benzoquinone monooxime was protonated in magic acid, ten peaks were observed in the ^{13}C NMR spectrum. The chemical shifts for C_1 and C_4 were, however, readily assigned, as discussed above. The eight remaining chemical shifts can be explained in terms of two structural isomers of **5,** designated as **5A** and **5B.**

A careful analysis of this system shows eight absorptions for C_2, C_3, C_5, and C_6 where the protonated ketone function affects C_3 and C_2 and/or C_5 and C_6. If the hydroxylamine group would have only affected C_2 and C_6 and the protonated

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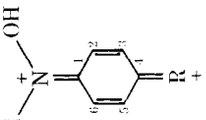
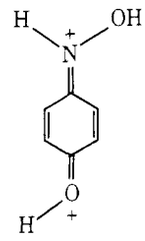
Table I. The ^1H NMR Chemical Shifts (δ) of Diprotonated Benzoquinone Monooximes [a]

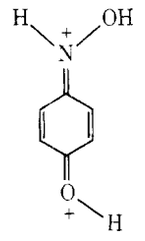


Structure	R	Substituent[c,d]	Registry no.	OH	NOH	NH	C_2	C_3	C_5	C_6	Other
5	4-OH		65355-17-1	14.3 (s)	12.1 (d)	13.5 (br)			8.1 (mult)		
6	4-OCH_3		65355-18-2		12.2 (d)[b]	13.8 (br)			8.4 (mult)		5.4 (s, OCH_3)
7	4-OH	6-CH_3	65355-19-3	13.8 (s)	12.0 (d)	13.1 (br)		8.6 (d)	8.0 (br)	7.8 (m)	2.8 (s, 6-CH_3)
8	4-OH	2,6-di-CH_3	65355-20-6	13.4 (s)	12.2 (d)	13.2 (br d)		7.5 (s)	7.5 (s)		2.7 (s, 2-CH_3), 2.9 (s, 6-CH_3)
9	4-OH	3- and 5-CH_3	64355-21-7	14.6 (s)	12.0 (d)	13.5 (br)		8.6 (mult)			2.7 (s, 3- and 5-CH_3)
10B	4-OH	5,6-di-CH_3	65355-22-8	14.1 (s)	12.0 (d)	13.2 (br d)	8.6 (d)	7.8 (d)			2.5 (s, 5-CH_3), 2.8 (s, 6-CH_3)
11	4-OH	3,5-di-CH_3	65355-23-9	13.7 (s)	11.5 (d)	12.9 (br)	8.3 (br s)		7.8 (br s)		2.4 (br s, 3- and 5-CH_3)
12A	4-OH	3,6-di-CH_3	65355-24-0	14.1 (s)	12.1 (d)	13.2 (br)	8.4 (br s)		7.5 (br s)		2.5 (s, 3-CH_3), 2.8 (s, 6-CH_3)

[a] The chemical shifts are referenced from external Me_4Si. [b] There are two peaks with a chemical shift difference of less than δ 0.1. [c] All of the spectra were measured at −60 °C. [d] All of the structures are derivatives of **2**.



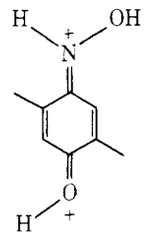
5A



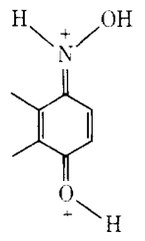
5B

ketone group C_3 and C_5, then the chemical shifts of the four carbons C_2, C_3, C_5, and C_6 of **5A** would also be similar to the corresponding ones of **5B,** and only four carbon absorptions would be observed. Thus, the two isomers **5A** and **5B** have different chemical shifts due to their geometry and the substituent effect of the hydroxylamine and protonated ketone groups.

The first approach used to assign the eight remaining carbon chemical shifts of **5** involved substituting methyl groups at the ring positions. Thus, the geometry of the isomers could be limited to specific structures still closely related to the complex spectra of the parent systems. For example, the substitution of methyl groups at the C_3 and C_6 positions of **12** resulted in the observation of six ^{13}C chemical shifts. Of the four possible isomers it can be assumed that **12A** is thermo-



12A



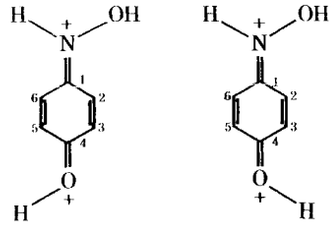
10B

dynamically more stable than the others for static reasons. The same argument holds in the case of diprotonated 5,6-dimethylbenzoquinone monooxime **10,** where structure **10B** should be the most stable.

The assignments of **7A, 7B, 9A,** and **9B** could be made using the chemical shift assignments of **10B** and **12A** as a comparison (Table II). Again applying the chemical shifts of **7A, 7B, 9A,** and **9B,** the peaks for **5A, 5B, 8A, 8B, 11A,** and **11B** were assigned. A majority of the ^{13}C NMR chemical shifts for **5A, 5B, 7A, 7B, 8A, 8B, 9A, 9B, 10B, 11A, 11B,** and **12A** were designated using this comparative method. However, the assignments of a number of the absorptions are interchangeable (**5A, 5B, 7A, 7B, 8B,** and **11B**), as indicated by asterisks and double asterisks, respectively, in Table II. The chemical shift differences are too small to assign these absorptions unequivocally by comparison, and a more specific approach such as substitution or selective labeling experiments would be necessary.

It has been consistently observed in our study that the hydroxylamino group shields C_2 relative to C_6. Thus, the hydroxylamino group should shield the carbon eclipsed by the hydroxyl relative to the carbon anti to it (**5**). This effect can be called the γ-substituent effect. A similar observation can be seen for the protonated ketone group. The C_5 position of **5A** and C_3 of **5B** are shielded relative to C_3 of **5A** and C_5 of **5B,** respectively. Again the protonated ketone group shields the carbons eclipsed with the proton relative to the anti carbon (**5**). These effects can be simply summarized by designating the carbons that are shielded relative to the deshielded ones as S and D, respectively. (It should be noted that S and D are presently only relative terms used to characterize the ^{13}C NMR patterns.) As mentioned before, if these are the only effects, in view of the experimental data, a total of six carbon

Table II. The ^{13}C NMR Chemical Shifts (δ) of Some Parent and Diprotonated Para-Substituted Nitrosobenzenes [a]

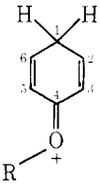


5A **5B**

Structure	R	Substituent	Registry no.	C_1	C_2	C_3	C_4	C_5	C_6	Other
5A[b]	4-OH			145.3 (s)[c]	136.8 (d)**	136.1 (d)	196.8 (s)	131.6 (d)	141.5 (d)**	
5B	4-OH			145.3 (s)	136.9 (d)**	133.9 (d)*	196.8 (s)	133.8 (d)*	141.2 (d)**	
6A	4-OCH_3			145.7 (s)	133.6 (d)	136.9 (d)	196.6 (s)	127.3 (d)	141.9 (d)	70.1 (q, OCH_3)
6B	4-OCH_3			145.7 (s)	137.4 (d)*	129.2 (d)	196.6 (s)	134.6 (d)	137.7 (d)*	70.1 (q, OCH_3)
7A	4-OH	6-CH_3		146.3 (s)	136.4 (d)**	135.8 (d)	195.3 (s)	129.9 (d)	157.2 (s)	17.8 and 17.6 (q, 6-CH_3)
7B	4-OH	6-CH_3		146.3 (s)	136.6 (d)**	133.4 (d)	195.3 (s)	132.0 (d)	156.4 (s)	
8A	4-OH	2,6-di-CH_3		146.0 (s)	155.5 (s)	133.8 (d)	192.1 (s)	129.2 (d)	158.5 (s)	17.9 (q, 6-CH) 25.7 and 25.6 (q, 2-CH_3)
8B	4-OH	2,6-di-CH_3		146.0 (s)	156.4 (s)	131.6 (d)*	192.1 (s)	131.3 (d)*	157.4 (s)	17.9 (q, 6-CH_3)
9A	4-OH	3-CH_3		145.4 (s)	132.4 (d)	149.4 (s)	197.2 (s)	131.6 (d)	141.3 (s)	16.4 and 15.8 (q, 3- and 5-CH_3)
9B	4-OH	5-CH_3		145.7 (s)	136.5 (d)	133.7 (d)	197.2 (s)	146.5 (s)	136.5 (d)	
10B	4-OH	5,6-di-CH_3		146.5 (d)	135.9 (d)	133.9 (d)	195.3 (s)	142.9 (s)	150.4 (s)	14.3 (q, 6-CH_3), 12.1 (q, 5-CH_3)
11A	4-OH	3,5-di-CH_3		145.4 (s)	132.1 (d)	140.4 (s)	197.9 (s)	143.0 (s)	137.7 (d)	16.7, 16.1, 16.1, 15.5 (q, 3- and 5-CH_3)
11B	4-OH	3,5-di-CH_3		145.4 (s)	133.2 (d)	146.5 (s)*	197.9 (s)	145.6 (s)*	136.5 (d)	
12A	4-OH	3,6-di-CH_3		146.2 (s)	131.9 (d)	148.8 (s)	195.6 (s)	129.8 (d)	157.0 (s)	7.5 (q, 6-CH_3), 16.1 (q, 3-CH_3)
13	2-OCH_3		65355-25-1	163.8 (s)	107.5 (d)	115.0 (d)	165.8 (s)	113.1 (d)	141.4 (d)	55.8 (q, OCH_3)
14	2-N-$(CH_3)_2$		65355-26-2	163.8 (s)	107.5 (d)	111.6 (d)	156.1 (s)	111.6 (d)	142.8 (d)	41.9 (q, $N(CH_3)_2$)
15a	4-N-$(CH_3)_2$		65355-27-3	145.4 (s)	126.8 (d)	129.8 (d)	160.3 (s)	129.8 (d)	132.2 (d)	47.2 (q, $N(CH_3)_2$)
16, 17	4-NOH(H)		65528-83-8 65528-84-9	148.2 (s)	126.8 (d)	129.8 (d)	148.2 (s)	126.8 (d)	129.8 (d)	

[a] The chemical shifts are referenced from external Me_4Si. Absorption values indicated by asterisks and double asterisks are interchangeable. [b] A and B refer to the geometry of the species. [c] Coupling determined by an off-resonance proton-decoupling experiment.

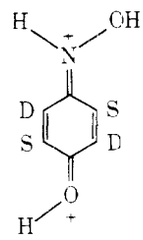
Table III. The ^{13}C NMR Chemical Shifts (δ) of Para-Protonated Phenol and Ortho-Substituted Anisoles [a]



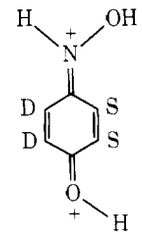
Structure	R	Substituent	Registry no.	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
18	H[c]		65355-28-4	40.3 (t)[e,f]	173.8 (d)	125.2 (d)	190.8 (s)	125.2 (d)	173.8 (d)		
19	CH_3[b]		37396-37-5	39.9 (t)	168.4 (d)	126.7 (d)	191.9 (s)	120.7 (d)	175.1 (d)	62.2 (q)	
	J_{C-H} (Hz)			126.0	169.3	174.6		173.4	170.5	152.3	
20	CH_3[c]	3-F	65354-79-2	39.6 (t)	144.4 (d)	153.6 (s)	184.3 (s)	121.5 (d)	175.8 (d)	63.6 (q)	
	J_{CF} (Hz)					261.9					
	J_{CCF}				12.8			12.9			
	J_{CCCF}			5.1							
21	CH_3[c]	3-Cl	65354-78-1	41.2 (t)	164.7 (d)	131.1 (s)	187.9 (s)	120.7 (d)	175.1 (d)	63.7 (q)	
	J_{CH} (Hz)			125.3	174.8			174.4	172.7	153.5	
22	CH_3[d]	3-CH_3 (C_8)	37145-56-5	39.4 (t)	164.9 (d)	135.6 (s)	191.0 (s)	120.1 (d)	173.5 (d)	62.0 (q)	15.1 (q)
	J_{C-H} (Hz)			127.6	173.3			172.4	167.2	152.4	130.6

[a] All chemical shifts are measured from external Me_4Si. [b] Measurements were obtained from ref 11. [c] These benzenium ions were made in HF–SbF_5 (1:1) in SO_2ClF at −60 °C. [d] This cation was made in HSO_3F–SO_2 at −60 °C. [e] Singlet (s), doublet (d), triplet (t), quartet (q). [f] The off-resonance assignments of s, d, t, or q only represent the C–H coupling and not long-range coupling. These were obtained from off-resonance or fully coupled experiments.

peaks would be observed, but secondary effects are also significant.

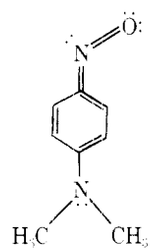


5A



5B

These secondary effects, which result in different ^{13}C NMR chemical shifts, are sometimes small and difficult to assign unequivocally. For example, the effect of a protonated carbonyl group on C_2 and C_3 of **5A** and **5B**, respectively, is too small to be designated. Protonated phenol shows no difference between C_2 and C_6 or C_3 and C_5, and protonated nitrosobenzene itself is unstable. Even diprotonated *p*-dimethylaminonitrosobenzene (**15**) showed no observable differences in the ^{13}C chemical shifts of C_3 and C_5.



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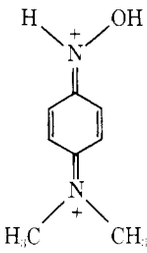
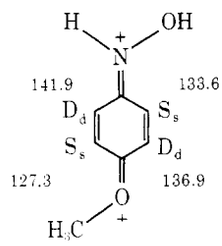


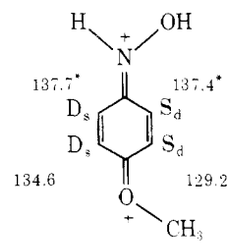
15a

It is known that the ^{13}C NMR chemical shifts of C_2 and C_6 and C_3 and C_5 are nonequivalent in para ring protonated anisole (**19**, Table III).[10,11] The ^{13}C NMR chemical shifts of **19** have not yet been assigned unequivocally. Therefore, a series of ortho-substituted anisoles were protonated and their ^{13}C NMR spectra measured (Table III). The substitution at the ortho position resulted in only one isomer in all cases. A comparison of the ^{13}C NMR chemical shifts and use of the fully coupled spectra for **19–22** resulted in the assignments given in Table III. The same chemical shifts for **19** were deduced and tentatively assigned based on previous work on the rearrangements of benzenium ions.[11]

The ^{13}C chemical shifts show that C_5 is shielded relative to C_3 of **19**. The same primary shielding effect is observed for the methyl carbon of the methoxy group eclipsed with the C_5 relative to the anti C_2. The secondary effect shows that C_2 is shielded relative to C_6. The secondary effects for simplicity will be designated as subscripts d and s. Application of this observation to **6** resulted in the assignments of the ^{13}C NMR chemical shifts shown for **6A** and **6B** in Table II. Similar



6A



6B

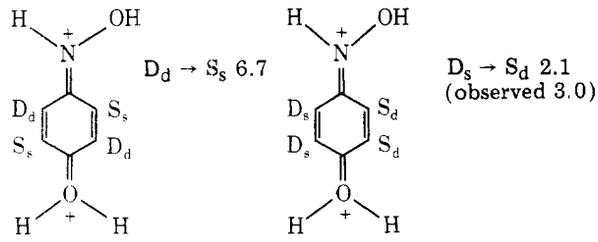
	$C_{2,6}$	$C_{3,5}$
$D_d \rightarrow D_s$	3.8	1.9
$S_s \rightarrow S_d$	−4.2	−2.3
$D_d \rightarrow S_d$	−4.5	−7.7
$S_s \rightarrow D_s$	4.1	7.3

considerations were also applied subsequently to **7A–12A** and **15**. In every case a good correlation was observed with the chemical shifts assigned on the basis of the comparison technique. Additionally, the ^{13}C chemical shifts for the carbons noted in Table II by double asterisks were also designated using this method. For example, whereas **6A** and **6B** were assigned tentatively in a qualitative manner, the present empirical method, however, can be used quantitatively.

Using **6A** and **6B**, the primary and secondary substituent effects can be calculated from the ^{13}C NMR chemical shifts of carbons C_2 and C_6, as well as C_3 and C_5, and are listed accordingly. For example, the secondary effect of the methoxy group can be estimated by the difference of chemical shifts of C_6 of **6A** and C_6 of **6B**, designated as $D_d \rightarrow D_s$, and of C_2 of **6A** and C_2 of **6B**, designated as $S_s \rightarrow S_d$, respectively. If the

effects are additive, the $D_d \rightarrow D_s$ difference should be equal in size but opposite in direction to the $S_s \rightarrow S_d$ difference. In this manner the remaining interchangeable ^{13}C chemical shifts of Table II were assigned (except for C_2 and C_6 of **6B**). The presently assigned ^{13}C chemical shifts showed the smallest overall deviations.

When benzoquinone dioxime was protonated and its ^{13}C spectrum was measured, only three carbon absorptions were observed, indicating that only one isomer was formed. Using the above discussed quantitative method of assignment and the proper $D_s \rightarrow S_s$ and $S_d \rightarrow S_s$ values, it was found that structure **17** best fits the data.

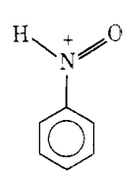


16 17

Structures **13A** and **14** were assigned only by the qualitative method. The C_2 and C_6 chemical shift assignments of **14** seem to be reversed from those reported by Grishin, Sergeev, Subbotin, and Ustynyuk.[12]

Discussion

Nitrenium, Onium, and Benzenium Ions. In the protonation of nitrosobenzene, there are three possible sites of protonation: O-protonation (**3**), N-protonation (**27**), and C-protonation (**28**). A resonance structure of **3** can be drawn where the formal charge is placed on the nitrogen (**3B**), thus



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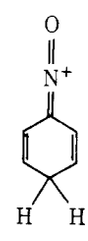

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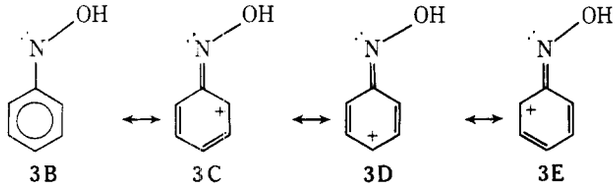


3B 3C 3D 3E

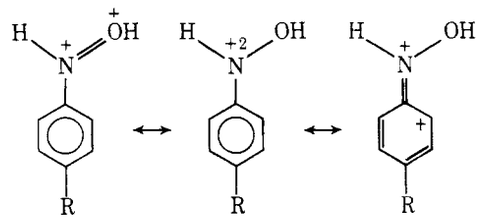
formally giving a nitrenium ion. Additionally, the phenyl ring would stabilize the positive charge by delocalization through structures **3C–E.** Thus, the overall structure of **3** combines the properties of an O-protonated nitroso compound, a nitrenium ion, and a benzenium ion.

Protonation on nitrogen would result in structure **27,** which can be considered similar to an ammonium compound. This compound would be primarily stabilized by the inductive effect due to the electronegativity of nitrogen. Stabilization by resonance contributors would not be expected.

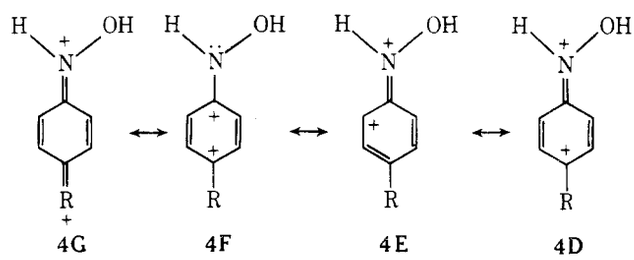
Protonation on the aromatic ring, as in **28,** would result in a benzenium ion whose primary stabilization is through the nitroso group. However, as the para position is substituted with a heteroatom, protonation can be excluded at this position.

When substituted nitrosobenzenes were protonated with magic acid in SO_2 solution, protons added formally at both the nitrogen and oxygen atoms of the nitroso group (Tables I and II), forming the diprotonated cations **4.** The diprotonation of the species was concluded from ^1H and ^{13}C NMR analysis of solutions. These dication species are similar to those proposed by Okamato and co-workers as intermediates in the strong acid-catalyzed reactions of nitrosobenzene.

The protonated dications **4** are stabilized by the combination of structures **3C–E** and **18,** and resonance structures **4A–E** can be written. Structure **4B** would be expected to



4A 4B 4C



4G 4F 4E 4D

contribute very little to the overall stabilization because of the two formal charges on nitrogen. Besides the above structures **4A** and **4C–E,** resonance structures **4F,** formally a 4 π system, and **4G,** stabilized by the heteroatoms, will contribute to the overall structure and stabilization of **4.**

From the ^{13}C NMR spectroscopic studies it is possible to clarify the structure of the diprotonated species. The ^{13}C NMR chemical shifts of C_1 in Table II are similar to those of the protonated aliphatic oximes[13] and those of C_4 to the para ring protonated phenol and anisole (Table III) and protonated aliphatic imines.[14] Additionally, a comparison of the ^{13}C chemical shifts of C_2, C_3, C_5, and C_6 of **6** and **7** with those of **18** and **19** showed a relative shielding for C_2 and C_6 and a deshielding of C_3 and C_5 for the dications (**6** and **7**) relative to the benzenium ions (**18** and **19**). For a dication one might have expected a much larger deshielding of these ring positions. The absence of significant charge in the ring indicates that the heteroatoms are stabilizing the dications by electron donation.[15] Thus, structure **4A** and **4G** contribute significantly to the overall structure. Some stabilization is provided by delocalization into the ring (**4C–F**) since diprotonated oximes and hydroxylamines similar to **4A** are exchanging under the same conditions.[13]

From previous studies on the structures of carbocations, particularly the styryl and α-methylstyryl cations, substitution at the para phenyl ring position resulted in an overall stabilization of the carbocation through electron delocalization. For example, if the parent styryl cation is compared to substituted *p*-methoxystyryl cations, the carbenium center is shielded and the ortho and para carbons are deshielded relative to those of the parent.[11]

From the substituted cations **5–12** (Table II) the general nature of the parent dictation **4** (R = H) can be inferred by using suitable comparisons. From the ^{13}C NMR data it was shown that structures **4A** and **4G** are the major contributors to the overall stabilization. Replacement of the hydroxyl, methoxy, and dimethylamino groups in the para position by hydrogen should increase the importance of **4A** relative to **4G.** The contributions of **4B–F** will remain about the same in the substituted and unsubstituted cases.

From our study it can thus be concluded that **4** (R = H) is stabilized primarily by **4A** with lesser contributions from **4C–E.** These onium–benzenium-type dications were used by Okamoto and co-workers to explain their products. The increased reactivity was justified by the strong benzenium ion character of **4.** Our work shows that these dications are primarily both a contribution of onium and benzenium ion nature, which results in stabilization of the overall structure and accounts for the increased reactivity observed in reported reactions. However, in sulfuric acid these dications (**4,** R = H) are probably in equilibrium with **27.** The nitrenium ion form **4B** contributes very little, if any, to the overall structure.

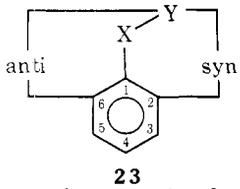
The ^{13}C NMR γ-Substituent Effect. The ^{13}C γ-substituent shielding effect in the gauche or syn configurations has been found for a variety of organic compounds such as alkanes, cycloalkanes, alcohols, amines, aldehydes, oximes, alkenes, alkylbenzenes, alkyl and aryl carbenium ions, and onium ions.[16] These observations make the γ-substituent effect a useful qualitative tool in the assignment of ^{13}C NMR spectra of stereochemically complex molecules.[17]

The basis of the γ-substituent effect was proposed by Grant and Cheney,[16c] who suggested that the interactions of the hydrogens bonded to the α and δ carbons (H–CCCC–H) were sterically perturbating the carbons, causing the shielding effect. Their model was based on nonbonded interactions, which depend on the bond angles and distances. Their theoretical model, developed from the work of Cignette and Allen, was then fitted to their experimental data, forming an empirical equation.

By definition, this model is not generally applicable to systems where nonbonded interactions are not possible, as in the cases of heteroatoms without directly attached hydrogens. In addition, it is generally assumed in hydrocarbons that the γ-shielding effect arises primarily from 1,4-gauche interactions. In contrast, from a variety of examples involving heteroatoms it was shown that the γ-shielding effect in the anti position is larger than that in the gauche position. Additionally, the results of some recent studies[16d,18,19] showed that a hydrogen–hydrogen nonbonded interaction does contribute to the shielding effect where it is applicable. However, it was concluded that other mechanisms play a role, i.e., such as bond angle distortions[19] and conformational effects,[20] in the γ-shielding effect in ^{13}C NMR spectroscopy. Despite the numerous examples of the γ-substituent effects, there is no quantitative method that can predict the relative magnitude for the different cases.

The ^{13}C NMR results of the two structural isomers of diprotonated benzoquinones, such as **5A** and **5B,** showed the nonequivalency of the C_2 and C_6 carbons as well as the C_3 and C_5 carbons. The ^{13}C NMR chemical shifts of these isomers were assigned by comparison with model compounds in Tables II and III, as well as through the use of empirical calculations from substituent effects. The origin for the nonequivalency of C_2 and C_6 and C_3 and C_5 and the basis of their assignments are called under the general term, the γ-substituent effect.

In all of the benzoid systems to be discussed it can be assumed that all of the atoms are in the same plane. Therefore, the γ-substituent effects observed from the ^{13}C NMR spectra result from the syn or anti configuration of a γ group relative to the group on the C_2 and C_6 carbons (**23**), respectively. In

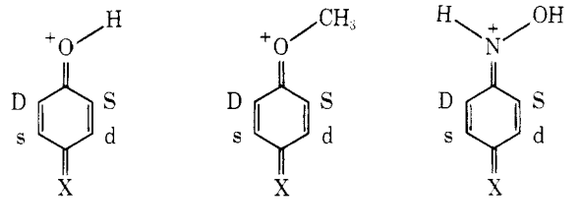


23

such aromatic systems where restricted rotation is slow the C_2 and C_6 carbons, and sometimes C_3 and C_5, of **23** are nonequivalent in the ^{13}C NMR spectra. The sources of the latter's nonequivalence (π polarization, induced dipole, or field effect) are not immediately obvious. It was therefore necessary to ascertain the assignment of these ^{13}C NMR chemical shifts as well as those for the C_2 and C_6 carbons.

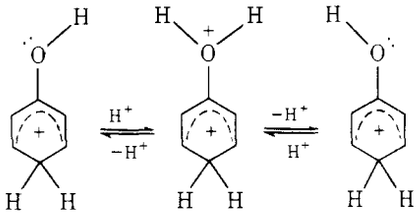
In the case of para ring protonated anisole and benzoquinone monooximes, the C_3 and C_6 carbons, respectively, were sterically blocked by the γ substituent (methyl group, fluorine or chlorine group). Thus, the C_2 carbon is always situated syn to the γ substituent. The absorption, therefore, could be unequivocally assigned by a comparison of the ^{13}C chemical shifts in Tables II and III.

From the assignments of the ^{13}C NMR spectra of the corresponding hydroxyl, methoxy, and hydroxylamino derivatives, the general pattern of relative shielding was determined and is shown in **24–26.** The letters S and s designate that these



24 **25** **26**

carbons are shielded relative to those labeled D and d, respectively. It is interesting to note, however, that the ring protonated phenol itself does not show any nonequivalence of C_2 and C_6 or C_3 and C_5. This apparent discrepancy is probably due to some exchange of the hydroxyl hydrogen with the strong protic acid since this hydroxyl proton was not observed in the ^1H NMR spectrum.



However, the effect of the hydrogen of the protonated ketone group in the diprotonated benzoquinone monooximes does show a relative γ-shielding effect of approximately 2 ppm in every case. It had been usually assumed previously that there was no γ-substituent effect for a hydrogen atom itself. The secondary effects (d, s) of the γ-substituent effects in the diprotonated benzoquinones were now also observed for the hydrogen atom. These effects were usually less than 1 ppm, which is much smaller than that observed in the case of protonated anisole (i.e., 6.7 ppm).

The average γ-substituent effects as well as the secondary effects of **24–26** are summarized in Table IV. Generally, the values show that the γ shielding and the secondary effects for a specific γ substituent produce the same values, indicating that the γ-substituent effect is additive. However, the different values of γ-substituent effect for the different γ substituents suggest that a different interaction mechanism(s) results in a different contribution to the overall effect.

The secondary effect had been previously observed in the ^{13}C NMR spectrum of **19.** Secondary effects have also been

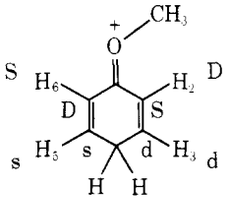


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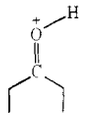
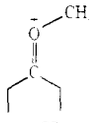
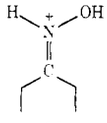
Table IV. Relative γ-Substituent Effects for Benzoid Cations

Function	γ effect (C_2 and C_6), ppm	Exp[b]	Secondary effect (C_3 and C_5), ppm	Exp[b]
 24	−2.3 ± 0.1	3	−0.2 ± 0.1	3
 25	−7.0 ± 1.0	3	−4.9 ± 1.9	3
 26	−4.6 ± 0.9	6	−1.8 ± 0.5 −2.2 ± 0.3[a]	6 5

[a] The 0.0-ppm value obtained from **15** was excluded from the average. [b] Number of experimental measurements.

noted in various other ring systems where restricted rotation produces an observable nonequivalency of ring carbons and hydrogens. However, they have not been attributed to the γ substituent.

Unlike the γ-substituent effects in saturated systems, the γ-substituent effects of these benzoid ring systems are observed in the ^1H NMR spectra. For example, the effect was observed in the ^1H NMR spectrum of the para ring protonated anisole. By substituting the C_3 of **19** with a blocking group, the methoxyl methyl group always positions itself syn to the C_2 carbon. Thus, it should be possible to assign the ^1H NMR chemical shifts in a manner similar to the ^{13}C NMR shifts. However, the differences found are approximately intermediary, and thus only a tentative assignment can be made with H_2 and H_3 being shielded relative to H_6 and H_5, respectively. This suggests that the secondary effects result from π polarization of the double bonds of the quinoidal structure **19** rather than an induced dipole or a field effect being operative. These results are, however, only tentative, and more unequivocal assignments of the ^1H and ^{13}C NMR spectra as well as a functional theoretical basis will be necessary before a generalized approach can be presented.

There are two anomalies which cannot be explained by the overall concept, i.e., the diprotonation of **13** and **14.** Since both compounds show the same discrepancy, only **14** will be discussed for simplicity. The ^{13}C NMR assignments of **13** and **14** are based on the assumption that the oxygen atom of the nitroso function shields C_2 relative to C_6. However, upon protonation it is expected that all of the ring carbons will be deshielded due to charge stabilization. In fact, the C_2, C_3, and C_5 carbons are deshielded; however, the C_6 carbon becomes shielded by 10.6 ppm. It was shown that the hydroxyl proton of a protonated ketone **23** relatively shields the syn ring carbon by 2.0 ppm. Thus, the hydroxyl proton of hydroxylamine cannot be the cause of the larger shieldings. The effect probably results from the fact that the mechanism of the γ-substituent effect of the nitroso function changes on protonation. Thus, the γ-substituent effect of the hydroxylamino group cannot be compared with that of the nitroso function since they are significantly different groups.

Planar systems, as studied above, offer a convenient way to investigate the γ-substituent effects in the syn and anti configurations. With unequivocal assignments of the ^1H and ^{13}C NMR spectra it will be possible to make more conclusive statements about the γ-substituent effect and its mechanism, including the observed secondary effects.

Conclusions

The NMR study of diprotonated benzoquinone monooximes (or *p*-nitrosophenols) showed that they are heteroatom protonated dications. Although protonation formally occurred on the adjacent nitrogen and oxygen atoms of the nitroso function, the dications are very stable since the charge is primarily delocalized between the distant hydroxylamine and hydroxyl groups. Thus the diprotonated benzoquinone monooximes are best described as containing a protonated oxime and a protonated ketone group. The contribution by any nitrenium ion form is minimal, if any, for the diprotonated benzoquinone monooximes.

The nature of N,O-diprotonated nitrosobenzene can be inferred to from that of the diprotonated benzoquinone monooxime. From a comparison of related substituted onium ions, the only expected difference is a change in charge delocalization. However, the absence of a charge stabilizing group results in a significant change in the electron density distribution as well as overall stabilization as reflected by the NMR shifts. Based on these considerations, N,O-diprotonated nitrosobenzene is an iminiumbenzenium dication, as proposed by Okamoto and co-workers.[6-8]

The planar diprotonated benzoquinone monooximes offer suitable models to study the γ-substituent effect of the syn and anti configurations. From these studies it was possible to show that even a hydrogen atom produces a γ-substituent effect. The hydrogen and methyl γ-substituent effects of a protonated or methylated carbonyl group or a protonated oxime group, respectively, were relatively measured by ^{13}C NMR spectroscopy and found to be constant and additive. Additionally, secondary effects of the nonequivalent C_3 and C_5 carbons related to the γ substituent were also observed and found to be consistent for each functionality. The ^{13}C NMR γ-substituent and secondary effects show a qualitatively predictable pattern. Thus, these systems provide a means of studying the γ-substituent effect. However, more work is necessary before these results can be placed on a more solid quantitative basis.

Experimental Section

Starting Materials. The precursor benzoquinone monooximes, benzoquinone dioxime, *p*-nitrosoanisole, and *p*-nitroso-*N,N*-dimethyaniline were prepared by known methods. The preparation of the benzoquinone monooximes was carried out by nitrosation of the appropriate phenol derivatives used in the work of Sternhell and Norris.[20] Benzoquinone dioxime was made from the condensation reaction of hydroxylamine and benzoquinone.[21] *p*-Nitroso-*N,N*-dimethylaniline was prepared by the nitrosation of *N,N*-dimethylaniline.[22] The esterification of *p*-nitrosophenol was carried out with methanol and sulfuric acid.[23]

Anisole and its ortho-substituted derivatives, used in the formation of the corresponding benzenium ions shown in Table IV, were commercially available (Aldrich Chemical Co.) and were used without further purification.

Preparation of Solutions of the Ions. Solutions of the dications (**5A–12A, 15,** and **16**) were prepared at −78 °C in a dry ice–acetone bath. The precursors (0.1–0.3 g) were dissolved in SO_2 (1 mL), and these solutions were carefully added to a well-stirred solution of HSO_3F–SbF_5 (1:1 molar, 2.0–3.0 g) dissolved in SO_2 (1 mL).

The benzenium ions shown in Table IV were prepared by the same method. However, the specific acids used in each case are different and are listed in Table IV.

Nuclear Magnetic Resonance Spectroscopic Studies. The ^1H NMR spectra were recorded on a Varian Associates Model A56-60 NMR spectrometer equipped with a variable temperature unit. All ^1H NMR chemical shifts were measured from external Me_4Si.

The ^{13}C NMR spectra were recorded on a Varian XL-100-15 NMR spectrometer equipped for proton decoupling, with a variable temperature unit and a 620/L computer with 16K data points. The instrument was run in the Fourier transform pulse mode with proton

decoupling of the fully coupled measurement obtained from a pulse routine that produces some nuclear Overhauser enhancement. The pulse width (H_1 field) in typical experiments was 2–25 σ, where a 42-μs pulse is equivalent to a 90° pulse. Acquisition times were between 0.3–0.8 s with pulse delays of 0–9 s depending on the experiment. The total number of transients for a suitable signal to noise ratio for each absorption varied from 100 to 7000 passes. The radio frequency was 25.16 MHz with the absorption referenced from 5% enriched external Me_4Si.

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Studies on Terpenes. 5. Synthesis of (+)-Hinesol and (+)-10-Epihinesol

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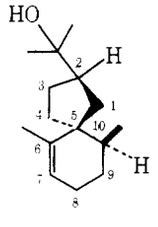
(−)-β-Pinene was converted into 9-methyl-6-carboethoxymethyl-7-oxatricyclo[4.3.0.0^{3,9}]nonane (**12**, R = H) which was homologated to the ester **15**. The ester **15** was rearranged to the diacetate **16** which on further elaboration gave **31**. Fragmentation of **31** as outlined (**9** → **10**) gave the spiro[4.5]decane **32**, which was readily transformed into a mixture of (+)-hinesol and 10-epihinesol. The synthesis correlates (−)-β-pinene with (+)-hinesol.

Since the revision of the structures of the vetivane sesquiterpenes[3] from hydroazulenes to spiro[4.5]decane skeletal types,[4] many syntheses of this unusual class of terpenes have been reported.[5] Only one synthesis of optically active spiro[4.5]decanes has been described.[6] Here we report the synthesis of (+)-hinesol (**1**)[23] from (−)-β-pinene as part of our



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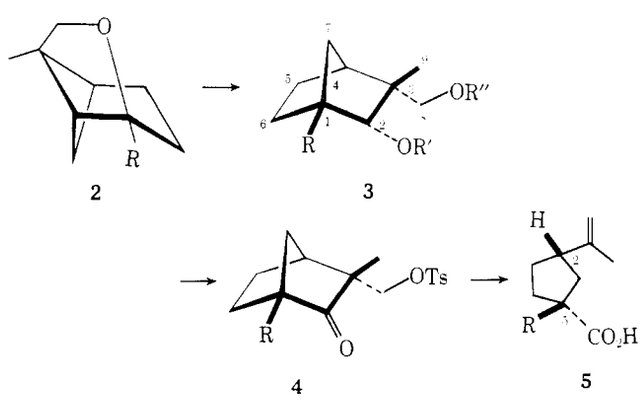
general program that led to the conversion of (−)-β-pinene into grandisol.[7]

The overall strategy of our approach was established by the observation that certain 7-oxatricyclo[4.3.0.0^{3,9}]nonane derivatives **2** can be rearranged to 8-substituted 1,3,3-trimethylnorbornane derivatives **3**. Subsequent fragmentation of the compound **4** to a cyclopentane derivative **5** provides a simple, yet effective way of establishing the correct absolute configuration at C-2 and C-5 in hinesol.[7,8] Scheme I summarizes this strategy. To provide a synthesis of (+)-hinesol (**1**) the substituent R in **2** must be capable of being elaborated to eventually become part of the cyclohexene ring of **1**.

The standard method of preparing 7-oxatricyclo[4.3.0.0^{3,9}]nonane derivatives[8,9] **2** involves the addition of Grignard reagents or organolithiums to (+)-nopinone (**6**) and subsequent intramolecular oxidation of the resulting products **7** to the ethers **2**. All attempts to introduce a suitable R group that contained all the requisite carbon atoms, namely a C_5 unit, were unsuccessful.[10] Extension of Scheme I to the spe-

Scheme I



2 3 4 5