anticipated as the internal motion would appear as a rotation of the whole molecule.

4. In the fourth and final case, we consider rapid Trp-Trp motion as well as fast RET then the situation is complex but related to the first case since reversible energy transfer reorients the emission dipoles. Some information of the properties of the Trp-Trp can be obtained from the fluorescence decay measurements. The decays for Trp, Trp-Ala, and Ala-Trp are generally nonexponential and depend on the pH of solution.[9,16] In Trp-Trp the decays are also nonexponential. Proton-transfer and charge-transfer quenching have been shown to describe the behavior of Trp, Ala-Trp, and Trp-Ala at neutral pH.[9,16] Lifetimes due to different rotamers have also been proposed.[32] Charge transfer is favored for Trp-Trp in Me_2SO or MeCN since the amino group is not protonated. The two decay times could be due to diffusional motion of the chromophore into the correct geometry for quenching; alternatively the two lifetimes could be due to different quenching rates of the two indole rings by the carbonyl group.

Conclusions

Both NMR and fluorescence anisotropy experiments clearly illustrate the differences in shape of the $\mathbf{1}_{LL}$ and $\mathbf{1}_{DL}$ diastereomers. We have postulated that the $\mathbf{1}_{DL}$ has a folded structure and $\mathbf{1}_{LL}$ a more open geometry with respect to the indole chromophores. The reorientational relaxation of **1** in glycerol–MeOH mixtures and in dihydric alcohol are far faster than anticipated by using stick limit boundary conditions; in fact the slip limit fits the data points fairly well. This "slip-like" type of behavior has been previously observed in glycerol and may be a consequence of the glycerol reorientation ocurring by large steps rather than by Brownian diffusion as a result of long-lived volume fluctuation in this liquid. **1** rotates with more freedom as a result of these fluctuations than in undecanol which orients by a small-jump diffusional process.[30] In glycerol–MeOH it is also possible that the two indoles in the molecule rotate during the excited state lifetime and contribute to the overall molecular rotation. This intramolecular motion would be aided by the freedom to rotational motion allowed in the glycerol–MeOH mixtures. The small P_0 values obtained from Perrin plots can be explained if the two indole chromophores emission dipoles are ~70° or ~110° to one another. Energy transfer between the two indole would be small compared to the excited-state lifetime when the chromophores have these geometries.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society. We are grateful to Dr. J. Feeney (NIMR, Mill Hill, London) for assistance in the interpretation of the NMR spectra.

Registry No. $\mathbf{1}_{LL}$, 81387-96-4; $\mathbf{1}_{DL}$, 81387-97-5; $\mathbf{1}_{DD}$, 81387-98-6; $\mathbf{1}_{LD}$, 81387-99-7; **2**, 24046-71-7; **3**, 16305-75-2; *Z*-L-Trp-OH, 7432-21-5; *Z*-D-Trp-OH, 2279-15-4; H-L-Trp-OMe-HCl, 26988-71-6; H-D-Trp-OMe-HCl, 41222-70-2; *Z*-Trp-Trp-OMe, 17689-58-6; *Z*-DTrp-Trp-OMe, 81444-73-7; *Z*-D-Trp-D-Trp-OMe, 81444-74-8; *Z*-Trp-D-Trp-OMe, 81444-75-9; cyclo(Trp-Trp), 20829-55-4.

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[32] Szabo, A. G.; Rayner, D. M. *J. Am. Chem. Soc.* **1980**, *102*, 554.

Sign Determination of Electron-Spin Distributions in Iminoxy Radical Analogues

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Abstract: Nickel-induced ^1H NMR contact shifts have been determined for β, γ, δ, and ϵ protons in a variety of oximes in which the molecular geometries are partially constrained by the oximino group. It is shown that these represent appropriate models for iminoxy radicals, with electron spin induced primarily in the nitrogen lone-pair orbital. Since this method directly provides the sign of the electron-spin density, it permits inference of the signs in the iminoxy radicals. It is pointed out that spin distributions in these radical analogues parallel those similarly determined in aliphatic and aromatic amines, thus indicating spin delocalization independence of the nature (σ or π) of the intervening bonds in the molecule.

The study of long-range ESR hyperfine splitting constants (hfsc's) has provided considerable insight into electron and electron-spin delocalization through σ frameworks and hence into the quantum mechanical integrals controlling these and related phenomena.[1] These data can be rationalized simplistically but usefully within the valence bond formalism, thus providing mnemonics for the prediction of the effect on spin densities of such variables as structure, conformation, substitution, etc. In developing a fuller picture of the mechanisms of spin delocalization, major advances have been made by studying the effect of molecular geometry on the ESR hfsc's particularly in rigid bicyclic radicals, by quantum mechanical analysis of the data, and by experimental determination of the sign of the spin density.[1]

Since the modes of spin delocalization are determined to a large extent by the orientation of the bonds making up the delocalization paths, it is necessary to be able to describe these paths unambiguously in terms of the relevant dihedral angles in that molecular fragment. The convention used for defining these angles, $\theta_\beta{}^C$, $\theta_\gamma{}^H$, etc., is illustrated in Figure 1 by using the nonplanar propyl fragment. Mechanisms of spin delocalization to α and β nuclei[2] have been well established[3] and, while considerable progress has been made with delocalization to nuclei more distant from the radical site, the difficulty in obtaining sufficient experiment data for certain regions of conformational space has been a limiting factor. In particular, data in the regions (180°, 0°) and (0°, 180°)

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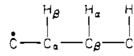
[1] For a recent thorough review of this subject see F. W. King, *Chem. Rev.*, **76**, 157 (1976).

[2] The nomenclature adopted here is the usual ESR convention, viz.



$$\dot{C}-\underset{}{\overset{H_\beta}{\overset{|}{C_\alpha}}}-\overset{H_\alpha}{\overset{|}{C_\beta}}-\overset{H_\delta}{\overset{|}{C_\delta}}$$

[3] (a) H. M. McConnell, *J. Chem. Phys.* **24**, 764 (1956); (b) R. Bersohn, *ibid.*, **24**, 1066 (1956); (c) H. S. Jarrett, *ibid.*, **25**, 1289 (1956); (d) H. M. McConnell and D. B. Chesnut, *ibid.*, **28**, 107 (1958); (e) B. Venkataraman and G. K. Fraenkel, *J. Am. Chem. Soc.*, **77**, 2707 (1955); (f) R. Bersohn, *J. Chem. Phys.*, **24**, 1066 (1956); (g) J. P. Colpa and E. de Boer, *Mol. Phys.*, **7**, 333 (1964).

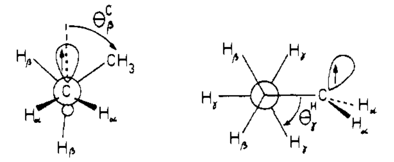


Figure 1. The definition of the terms $\theta_\beta{}^C$ and $\theta_\gamma{}^H$ for a propyl radical with tetrahedral radical site.

are scarce, largely because suitable molecules are hard to construct.

Iminoxy radicals possess the structural features necessary to provide some of these data. These radicals are stable, capable of generation from a wide variety of ketones and have been shown to be σ radicals with a high spin density in a nonbonding hybrid orbital localized substantially on nitrogen.[4] Because of the high spin density at this atom and due to the directionality of the spin-containing orbital, it is not surprising that this class of radicals has yielded a plethora of data pertaining to long-range hfsc's and hence to a better understanding of the phenomenon of spin delocalization. However, these radicals have stubbornly resisted spin density sign determinations.

Contact shift studies have been extremely useful in supplying information regarding the sign of the spin density in a variety of paramagnetic species. We[5,6] and others[7-14] have found the technique of adding bis(acetylacetonato)nickel(II), hereafter referred to as Ni(acac)$_2$, to diverse classes of organic compounds to be particularly useful in this context. Classes of compounds amenable to this treatment include aliphatic[6,8,9,15] and aromatic[10,11,13,16,17] amines and imines,[7,10,12,18] oxides,[19] phosphines,[20] nitriles,[18] isocyanides,[20] oximes,[16] and nitrones.[21]

In view of the ability of Ni(acac)$_2$ to induce spin in the nonbonding orbitals of amines, we examined whether oximes might be induced to yield information pertinent to the iminoxy radicals, or, alternatively, since amine oxides from π complexes,[19] whether they might yield information related to the corresponding π radicals. In this paper we report that (1) oximes do exhibit large characteristic chemical shift changes upon addition of Ni(acac)$_2$, (2) these shifts are in good agreement with spin densities calculated by UHF methods, (3) spin is induced essentially only in the σ framework, (4) there appears to be negligible contribution to these shifts from pseudocontact interactions, and (5) these act as useful models from which spin distributions (both sign and magnitude) in the iminoxy and other σ radicals might be deduced.

Experimental Section

Materials. The Ni(acac)$_2$ was purchased from Ventron Corp. and was obtained in an anhydrous form by heating in vacuo at 61 °C for at least 15 h. Chloroform-*d* was obtained from Merck Sharp and Dohme of Canada Limited. Tetramethylsilane (Me$_4$Si) was obtained from Stohler Isotope Chemicals. All oximes were either commercially available or were prepared by standard techniques; their identity and purity were determined by conventional spectroscopic methods.

NMR Measurements. All spectra were recorded on a Perkin-Elmer R20B spectrometer with a probe temperature of 35 °C. The proton resonance shifts were measured relative to an internal Me$_4$Si reference to eliminate bulk susceptibility shifts, and measurements were made by using a Takeda-Riken TR-3824X frequency counter. Two methods were used for determining the induced shifts. In one, a solution of the oxime in chloroform-*d* (ca. 1 M) was prepared, and its spectrum was recorded. To this was added increasing amounts of Ni(acac)$_2$, and each time the spectrum was recorded. Relative shifts[22] were obtained by plotting the chemical shifts against the Ni(acac)$_2$:amine ratio for at least six different concentrations. A linear least-squares regression analysis of the data provided a slope which was equated to the relative isotropic shifts. The second method was to utilize the above data but to plot the shifts of all but one proton relative to the shift of that remaining proton. This procedure also yields the relative shift values but eliminates errors due to uncertainties in the amounts of Ni(acac)$_2$ or amine used and invariably gave good straight lines[24] with smaller standard deviations. All data reported in this paper were determined by this method, but in those cases where comparisons were made between the two methods, the results were experimentally indistinguishable.

Results and Discussion

The isotropic shift may be a composite term to which two major contributions should be considered: a Fermi contact term and a dipolar term. The Fermi contact shift for a nucleus, N, is directly proportional to the ESR hfsc for that nucleus[28]

$$\sigma_{\mathrm{con}}{}^{\mathrm{N}} = -a^{\mathrm{N}}(\gamma_e/\gamma_n)\beta_e g_e S(S+1)/3kT$$

where a^{N} is related to the spin density at the nucleus by the expression[29]

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[4] R. O. C. Norman and B. C. Gilbert, *J. Phys. Chem.*, **71**, 14 (1967), and references cited therein.

[5] G. R. Underwood and H. S. Friedman, *J. Am. Chem. Soc.*, **96**, 4089 (1974).

[6] G. R. Underwood and H. S. Friedman, *J. Am. Chem. Soc.*, **96**, 4989 (1974).

[7] D. Doddrell and J. D. Roberts, *J. Am. Chem. Soc.*, **92**, 6839 (1970).

[8] (a) T. Yonezawa, I. Morishima, and Y. Ohmori, *J. Am. Chem. Soc.*, **92**, 1267 (1970); (b) I. Morishima and K. Yoshikawa, *ibid.*, **97**, 2950 (1975).

[9] (a) M. Ohashi, I. Morishima and T. Yonezawa, *Bull. Chem. Soc. Jpn.*, **44**, 576 (1971); (b) I. Morishima, K.; Okada; M. Ohashi, and T. Yonezawa, *Chem. Commun.*, 33 (1971).

[10] I. Morishima, T. Yonezawa, and K. Goto, *J. Am. Chem. Soc.*, **92**, 6651 (1970).

[11] K. Tori, Y. Yoshimura, and R. Muneyuki, *J. Am. Chem. Soc.*, **93**, 6324 (1971).

[12] I. Morishima, K. Okada, and T. Yonezawa, *J. Am. Chem. Soc.*, **94**, 1425 (1972).

[13] (a) L. M. Stock and M. R. Wasielewski, *J. Am. Chem. Soc.*, **94**, 8276 (1972); (b) *ibid.*, **95**, 2743 (1973); (c) *ibid.*, **96**, 583 (1974).

[14] L. M. Stock and P. E. Young, *J. Am. Chem. Soc.* **94**, 7686 (1972).

[15] I. Morishima, K. Okada, T. Yonezawa, and K. Goto, *J. Am. Chem. Soc.*, **93**, 3922 (1971).

[16] R. W. Kluiber, W. deW. Horrocks, Jr., *Inorg. Chem.*, **6**, 430 (1967).

[17] T. Yonezawa, I. Morishima, Y. Akana, and K. Fukuta, *Bull. Chem. Soc. Jpn.*, **43**, 379 (1970).

[18] R. H. Holm, G. W. Everett, and W. W. deW. Horrocks, Jr., *J. Am. Chem. Soc.*, **88**, 1071 (1966).

[19] R. W. Kluiber and W. deW. Horrocks, *J. Am. Chem. Soc.*, **88**, 1399 (1966).

[20] W. D. Horrocks, Jr., R. Craig Taylor, and G. N. LaMar, *J. Am. Chem. Soc.*, **86**, 3031 (1964).

[21] G. R. Underwood, D. M. Eastman and K. El Bayoumy, unpublished results.

[22] It could be argued that the absolute shift values at a known nickel concentration contain more information than do these relative shifts. It has been shown[23] that the absolute values are dependent upon both the equilibrium constant for complexation and the intrinsic shift of the fully complexed species. These two terms can be separated,[23] but the procedure is neither easy nor precise. Moreover, the intrinsic shifts are dependent on the amount of spin transferred to the nitrogen lone pair orbital and or the *Q* value describing the efficiency of subsequent transmission of spin from this orbital to the nucleus in question. We are concerned here only with those factors influencing this latter quantity and hence the use of the relative values is most useful.

[23] J. W. Rakshys, *Inorg. Chem.*, **9**, 1521 (1970).

[24] At the outset, it appeared probable that more than one complexed species might be involved in solution. However, consider two protons H_a and H_b in the oxime having shifts σ_{ai} and σ_{bi}, respectively, in the complex C_i. The observed shifts relative to the diamagnetic precursors are given by $\Delta\nu_a = \sum_i F_i\sigma_{ai}$ and $\Delta\nu_b = \sum_i F_i\sigma_{bi}$, where F_i is the molar fraction of the oxime in the form C_i. The ratio of the shifts will be $\Delta\nu_a/\Delta\nu_b = \sum_i F_i\sigma_{ai}/\sum_i F_i\sigma_{bi}$ and for a given pair of protons it might be expected that the ratio σ_{ai}/σ_{bi} should be different for each adduct C_i. Thus, with increasing Ni(acac)$_2$ concentration, the plot of $\Delta\nu_a$ vs. $\Delta\nu_b$ would show complex (nonlinear) behavior. Such a situation has been observed, for example, in solutions of imidazole and Co(Im)$_6$ClO$_4$)$_2$.[25] If, however, a plot of $\Delta\nu_a$ vs. $\Delta\nu_b$ yields a straight line, one of two conditions must obtain: (a) Only one adduct is formed with the substrate, in which event $\sigma_a/\sigma_b = \Delta\nu_a/\Delta\nu_b$. This evidently is the case for the complexation of Ni(acac)$_2$ with many amines.[26] (b) More than one type of adduct is formed, but the ratio σ_{ai}/σ_{bi} is independent of the nature of complexation in these species. This has been shown to be the case for the reaction of nickel(II) diethyl dithiophosphate with several aliphatic and cyclic secondary amines[27] and suggests that, in those complexes, the geometric requirements for the relative induced shifts in all complexed species is the same. In either event a linear plot of $\Delta\nu_a$ vs. $\Delta\nu_b$ gives easily interpretable data, and in all cases reported here no deviation from linearity in such plots could be detected.

[25] M. Wicholas, R. Mustacich, B. Johnson, T. Smedley, and J. May, *J. Am. Chem. Soc.*, **97**, 2113 (1975).

[26] A linear plot of $\Delta\nu$ vs. (Ni(acac)$_2$)/(amine) is suggestive of 1:1 complexation under the conditions of the experiment as also in a linear plot of $\Delta\nu^{-1}$ vs. (amine)$^{-1}$.[5]

[27] M. M. Dhingra, G. Govil, and C. R. Kanekar, *J. Magn. Reson.*, **6**, 577 (1972).

[28] H. M. McConnell and R. E. Robertson, *J. Chem. Phys.*, **29**, 1361 (1958).

$$a^N = (8/6S)g_{av}\beta_e g_n\beta_n|\psi(0)|^2$$

Thus it would be expected that this term should correlate well with ESR hfsc's of structurally similar radicals and with spin densities calculated by appropriate unrestricted Hartree–Fock calculations on open-shell model systems. This type of agreement has been taken as strong evidence for the dominance of the Fermi contact term in the shifts induced by $Ni(acac)_2$ in a wide range of organic bases.[30]

On the other hand the dipolar contribution, which is of prime importance for the lanthanide shift reagents, is proportional to the geometric term $(3\cos^2\theta - 1)/r^3$ and shows more readily predictable behavior. The complexation of tris(dipivaloylmethanato)europium, $Eu(dpm)_3$, with some oximes has been reported,[31,32] and in all cases downfield shifts of the proton resonances were observed. A plot of the induced shifts vs. the logarithm of the oxygen-to-proton distance yielded[32] a straight line of slope 2.3, typical agreement for a dominant pseudocontact interaction. By contrast, the present study gave both upfield and downfield shifts bearing no obvious relationship to those obtained by using $Eu(dpm)_3$ but with distinct similarities to the known ESR hfsc's for the corresponding iminoxy radicals.

If the shifts are purely contact in nature, then the ratio of the observed shifts corresponds directly to the relative contact shifts and hfsc's

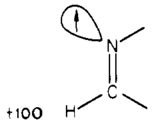
$$\Delta\nu_a/\Delta\nu_b = \sigma_{con}{}^a/\sigma_{con}{}^b = a^a/a^b$$

But since the ESR hfsc is given by

$$a^N = Q^N\rho$$

where ρ is the spin density at the "radical site" and Q^N is a measure of the efficiency of spin delocalization to the nucleus N, then $\Delta\nu_a/\Delta\nu_b = Q^a/Q^b$ provided that nuclei a and b are in the same substrate molecule. In order to make comparisons between protons in *different* molecules, it is necessary to assume the constancy only of Q for two nuclei in similar environments. This has been shown to be a valid assumption for a wide variety of paramagnetic species, and the consistency of results obtained by using this assumption certainly appears to justify its use in the present instance.[33]

In previous work we have arbitrarily assigned a value $Q^H = +100$ to a β proton[5,6] located at $\theta_\beta{}^H = 0°$ relative to the nitrogen lone pair, and this assignment is made for all aldoximes possessing that structural fragment (**1**). From this one reference value it is then possible to derive experimentally a self-consistent set of Q^H values for the protons in all oximes.



1

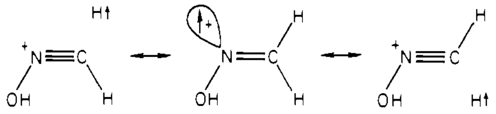
Oximes are known to be configurationally stable, thus giving rise to syn–anti isomerism in these derivatives of unsymmetrical aldehydes and ketones. In the following discussion, because of the overwhelming importance of the orientation of the nitrogen lone pair, we will use the terms cis and trans to describe the location relative to the lone pair.

Assignment of Shifts. Formaldoxime. The NMR spectrum of formaldoxime consists of three resonances: the hydroxylic proton at δ 9.15[34] and an AB quartet, J = 8.6 Hz, at δ 6.42 and 7.05. The spectrum of this compound has been reported previously,[35] and the most upfield absorptions were assigned to the cis proton on the basis that this proton resonates ca. 0.7-ppm upfield from its counterpart in all syn–anti aldoxime pairs.[36]

Upon addition of $Ni(acac)_2$ both resonances moved downfield with the ratio of the induced shifts being

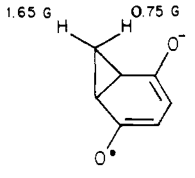
$$\Delta\nu_{trans}/\Delta\nu_{cis} = 2.05 \pm 0.04$$

Thus Q^H for the trans proton is assigned the value of +205. The downfield shifts (positive spin density) require that the ligand has σ, and not π, radical character. The experimental shifts and spin density signs are consistent with hyperconjugation (**2**) being the mechanism of delocalization of spin to the β protons with more efficient transfer to the trans proton than to the cis, an observation consistent with previous calculations.[37] Comparable experimental data are not available for the corresponding iminoxy radical which appears to be too unstable for ESR study, but the constancy of the β proton hfsc's in iminoxy radicals in general suggests that these values should be 15 and 6 G, respectively,[4] both values presumably having a positive sign. In the structurally related vinyl radical,[38] β-proton hfsc assignments of 64 and 32 G have been made, and, although the sign and greater magnitude for the proton at $\theta_\beta{}^H = 180°$ has not been demonstrated unequivocally, these results do appear to be in excellent agreement with our own.



2b **2a** **2c**

This knowledge of the efficiency and sign of spin transfer from a nonplanar radical site should be of use in assessing the facility of transmission of spin from hybrid orbitals within molecular fragments. For example, in the radicals **3**,[39] **4**,[40] and **5**[41] in which direct unpaired electron delocalization to the γ protons (shown) is forbidden by the symmetry of the singly occupied molecular orbitals, it has been suggested that spin polarization (**6b**) places spin in the C–C_α bonds. Further communication of this spin information to the C_β–H_γ bond (**6c**,**d**) might reasonably be ex-



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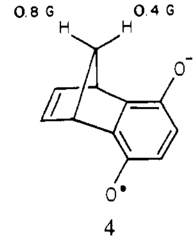

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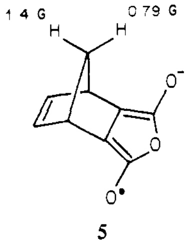

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(29) All symbols have the usual meaning, see R. S. Drago, J. I. Zink, R. M. Richman, and W. D. Perry, *J. Chem. Educ.*, **51**, 371 (1974).

(30) (a) R. J. Fitzgerald and R. S. Drago, *J. Am. Chem. Soc.*, **90**, 2523 (1968); (b) T. Yonezawa, I. Morishima, and Y. Ohmori, *ibid.*, **92**, 1267 (1970); (c) I. Morishima, T. Yonezawa, and K. Goto, *ibid.*, **92**, 6651 (1970); (d) W. deW. Horrocks, Jr., and D. L. Johnson, *Inorg. Chem.*, **10**, 1835 (1971); (e) K. Tori, Y. Yoshimura, and R. Muneyuki, *ibid.*, **93**, 6324 (1971); (f) M. M. Dhingra, G. Govil, and R. Kanekar, *J. Magn. Reson.* **6**, 577 (1972); (g) R. E. Cramer, *Inorg. Chem.*, **11**, 1019 (1972); (h) I. Morishima, K. Okada, and T. Yonezawa, *J. Am. Chem. Soc.*, **94**, 1425 (1972).

(31) Z. W. Wolkowski, *Tetrahedron Lett.*, 825 (1971).

(32) K. D. Berlin and S. Rengaraju, *J. Org. Chem.*, **36**, 2912 (1971).

(33) Under the influence of extreme perturbation such as highly electronegative substituents, however, this assumption may not be valid: L. M. Stock and M. R. Wasielewski, *J. Am. Chem. Soc.*, **97**, 5620 (1975).

(34) Concentration dependent.

(35) B. L. Shapiro, S. J. Ebersole, and R. M. Kopchik, *J. Mol. Spectrosc.*, **11**, 326 (1963).

(36) (a) W. D. Phillips, *Ann. N.Y. Acad. Sci.*, **70**, 817 (1958); (b) E. Lustig, *J. Phys. Chem.*, **65**, 491 (1961).

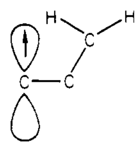
(37) G. R. Underwood and R. S. Givens, *J. Am. Chem. Soc.*, **90**, 3173 (1968).

(38) (a) R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, **39**, 2147 (1963); (b) R. W. Fessenden, *J. Phys. Chem.*, **71**, 74 (1967).

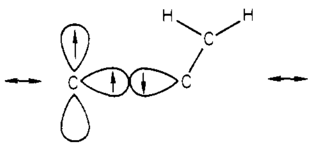
(39) (a) G. A. Russell, J. R. Dodd, T. Ku, C. Tanger, and C. S. S. Chung, *J. Am. Chem. Soc.*, **96**, 7255 (1974); (b) G. A. Russell, T. Ku, and J. Lokensgard, *ibid.*, **92**, 3833 (1970).

(40) K. Kosman and L. M. Stock, *ibid.*, **91**, 2011 (1969).

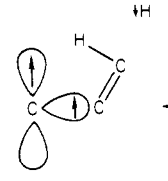
(41) S. F. Nelsen and E. D. Seppanen, *ibid.*, **89**, 5740 (1967).



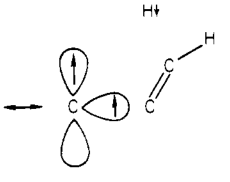
6a



6b



6c



6d

pected to parallel the delocalization of spin from the nitrogen lone pair to the C_α–H_β bonds in formaldoxime (**2b**,**c**). The ratios of spin densities for the two hydrogens at $\theta_\gamma^H = 180°$ and $\theta_\gamma^H = 0°$ are ±2.2, ±2.0, and ±1.8, respectively, in excellent agreement with the value of +2.05 obtained here. Such agreement lends credence to this proposal, and it is therefore predicted that the spin densities at the γ protons of **3**, **4**, and **5** will be negative.[42]

Acetaldoxime. The NMR spectra of both the syn and anti isomers of acetaldoxime can be observed in chloroform-*d* at the probe temperature (35 °C), and unequivocal assignment of the resonances has been made.[36] The syn/anti ratio is 0.6. Upon addition of $Ni(acac)_2$ both aldehydic proton resonances moved to lower fields with that of the syn isomer[44] showing by far the greater shift ($\Delta\nu_{syn}/\Delta\nu_{anti} = 10.2$). It is worthy of note that this suggests vastly differing efficiences of complexation of the $Ni(acac)_2$ with the two diastereomers. This should be borne in mind when shifts of this kind are used in conformational analysis. Previous workers[9,15] have implicitly assumed equal complexation of $Ni(acac)_2$ with both axial and equatorial orientations of the nitrogen lone in piperidines, an assumption which has been sharply criticized.[45] From the present work it is apparent that such criticism is justified and that neglect of this factor could lead to seriously erroneous conclusions. For the syn isomer the ratio of the shifts $\Delta\nu_{trans}^{CH_3}/\Delta\nu_{cis}^{H} = 0.336$ which, coupled with the above assignment of $Q_{cis}^{H} = +100$, yields $Q_{cis}^{CH_3} = -44.6$. Similarly $Q_{trans}^{CH_3} = -33.6$. These results are compared in Figure 2 with corresponding ESR results for the iminoxy radicals and with calculated spin densities. Although only modest agreement is obtained between these data and the hfsc's for the iminoxy radicals, there is a distinct similarity which will become more obvious as other oximes are discussed.

Acetone Oxime. The Q values for the methyl hydrogens of the acetaldoximes were assigned on the assumption that the aldehydic protons should have the same values as their counterparts in formaldoxime. Carrying this assumption further to acetone oxime and assuming that the methyl proton shifts should be the same as in the acetaldoximes, the ratio of shifts for the two methyl groups should be

$$\Delta\nu_{cis}^{CH_3}/\Delta\nu_{trans}^{CH_3} = -44.6/-33.6 = 1.32$$

At 60 MHz the methyl resonances appeared as one unresolved absorption at δ 1.89. Upon addition of $Ni(acac)_2$ however both resonances moved upfield and a separation could be effected. The ratio of the Q values was found experimentally to be +1.14 ± 0.013 (both values negative), which is in good agreement with the anticipated value, thus providing a useful internal check of our assignments. We therefore take the Q values for the two methyl groups to be $Q_{trans}^{CH_3} = -35.5$ and $Q_{cis}^{CH_3} = -40.3$.

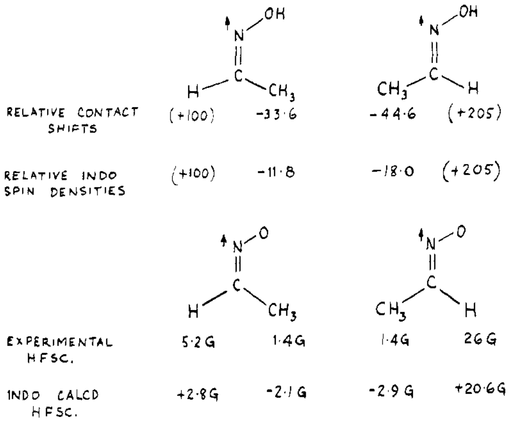
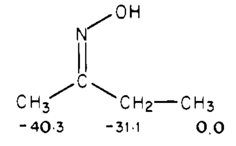


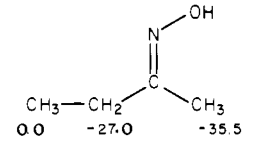
Figure 2. A comparison of the signed contact shifts obtained for the oximes, the experimental ESR hfsc's for the corresponding iminoxy radicals, and relative hydrogen 1s orbital spin densities calculated for the 1-hydroxypropenyl radical by the method described in the text and for the iminoxy radicals, taken from M. F. Chiu, B. C. Gilbert, and B. T. Sutcliffe, *J. Phys. Chem.*, **76**, 553 (1973).

The larger magnitude for $Q_{cis}^{CH_3}$ rather than for $Q_{trans}^{CH_3}$ may appear surprising in view of the considerable success of the empirical W plan[46] in assigning ESR hfsc's. However, it should be borne in mind that several mechanisms contribute to the total spin density at the γ proton,[5] and those protons conforming to the W plan are normally associated with large *positive* spin densities. In the present case, with methyl groups only partially constrained (θ_β^c) to the W-plan arrangement, the average spin density at the γ protons is negative and the observation of the least negative value for $Q_{trans}^{CH_3}$ is therefore in complete harmony with the W-plan mnemonic. In the ESR spectrum of the acetone iminoxy radical equal hfsc's of 1.4 G have been reported for all six hydrogens and it would not be expected that the 14% difference determined here could be detected in the ESR experiment.

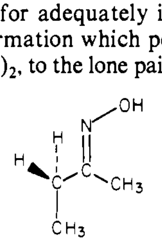
2-Butanone Oxime. Both isomers of the oxime could be detected with a syn/anti ratio of 2.6. Assignment of the pertinent resonances has been made previously,[36] and the proton contact shifts were determined as being those shown in **7a**,**b** with the methyl proton shifts being assumed equal to the corresponding shifts in acetone oxime. The trans methylene protons ($\theta_\beta^c = 180°$) have a value which is significantly smaller than that obtained for the freely rotating (θ_γ^H) methyl group in the same situation. This seems to be accounted for adequately in terms of preferential population of the conformation which permits easiest approach of the spin label, $Ni(acac)_2$, to the lone pair, viz., **8**. In substituted pyridines having this structural fragment a similar decrease has been observed[5] and this has been attributed to a positive contribution (**9**) to the spin density being favored for the (0°, 0°) conformation.



7a



7b



8

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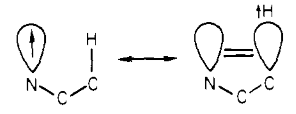
[42] The more efficient transmission of spin to the trans proton appears to be explicable on a theoretical basis as resulting from *lesser* overlap of the nonbonding orbital with the carbon hybrid orbital making up that C–H bond.[43]

[43] F. Weinhold and T. K. Brunck, *J. Am. Chem. Soc.* **98**, 3745 (1976).

[44] To avoid confusion we use the terms syn and anti only to refer to the stereochemistry of the oxime. The location of a particular atom will be designated by the appropriate dihedral angles or as being cis or trans to the lone pair.

[45] I. D. Blackburne, A. R. Katritzky, and Y. Takeuchi, *J. Am. Chem. Soc.*, **96**, 682 (1974).

[46] G. A. Russell in "Radical Ions", E. T. Kaiser and L. Kevan, Eds., Interscience, New York, 1968, Chapter 3.

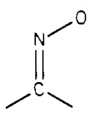


9a 9b

From the small Q values found for the methylene protons in 2-butanone oxime and the increased crowding, anticipated in 3-pentanone oxime, small shifts were to be expected in the latter compound. Although distinctly negative spin densities were apparent, it is unfortunate that the shifts were too small to permit a meaningful comparison with the Q values obtained in 2-butanone oxime.

Cyclohexanone Oxime. Extension of these studies to the cyclic ketoximes is not as easy nor as satisfying since there are no protons in the cyclic series with which direct comparison can be made. For this reason recourse was made to calculated spin densities. The INDO approximate UHF-SCF calculations have proven extremely popular (though somewhat less reliable) for the calculation of spin densities in paramagnetic molecules. In particular we have examined fairly closely the variation of γ-hydrogen spin densities calculated by this method as a function of structural and conformational changes[47] and have compared these data with corresponding experimental and ab initio[48] spin densities. Generally the INDO method gives satisfactory results except in the (0°, 0°) region where this method tends to underestimate the amount of α spin when compared with both experimental values[6] and more sophisticated theoretical methods.[48]

In reference to $Ni(acac)_2$-induced contact shifts it has frequently been found that best agreement between experiment and the calculations is obtained by replacing nitrogen with an uncharged trivalent carbon. For the present purposes, therefore, three model spin labels were examined for suitability: the iminoxy function, the radical cation derived from the oxime (σ radical), and the 1-hydroxyvinyl radical. We have found that the calculated spin densities at the β and γ protons are virtually independent of substitution at the β-carbon, and in the interest of economy we have performed most of our calculations on acetaldehyde with the carbonyl group replaced by one of these labels, **10**, **11**, or **12**.



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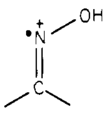

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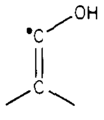


12

The α-hydroxy vinyl label gave clearly the best results, and all subsequent discussion will refer to this system. Although there was, as expected, some dependence of the spin densities on the various bond lengths and bond angles the following values were used: $C{-}C = 1.54$ Å; $C{=}C = 1.30$ Å; $C{-}O = 1.36$ Å; $C{-}H = 1.08$ Å; $OH = 0.96$ Å; $H{-}O{-}C = 109.5°$; $C{=}C{-}H = 120°$; $C{-}C{-}H = 109.5°$; $C{=}C{-}O = 120°$. After numerous attempts to refine this geometry, it was considered both unnecessary and undesirable to deviate from these reasonable values since, over even relatively wide ranges of bond angles and bond lengths, the general form of the spin density dependence on $\theta_\gamma{}^H$ remained essentially unchanged both for the cis and for the trans methyl protons. Thus spin density variations can be estimated most adequately from this approximate geometry even though the absolute values (which do not concern us here) may be somewhat in error.

Figure 3 gives the γ-hydrogen spin densities calculated for the 1-hydroxy-1-propenyl radical with the broken section of these lines referring to the uncertain region mentioned above. In this region more positive values might be expected. For the computation of spin densities at the hydrogens of the freely rotating methyl group, the calculated spin density was integrated over all conformations, with equal weight given to each conformation.

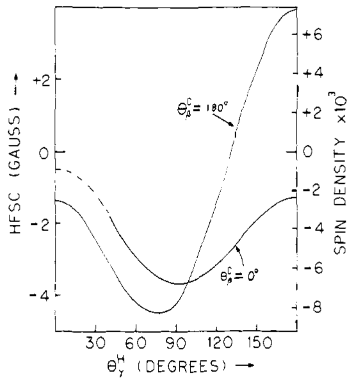
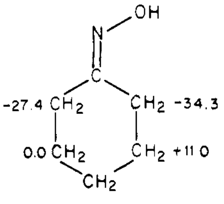


Figure 3. The INDO calculated γ-hydrogen spin densities determined for the 1-hydroxy-1-propenyl radical, expressed as a function of the dihedral angle $\theta_\gamma{}^H$ for the two alternative values of $\theta_\beta{}^C$. The broken section of the curve is expected, from previous studies, to be somewhat inaccurate.

For the cyclohexanone iminoxy radical it has been established that rapid ring inversion is occurring at room temperature[42] and apparently this is also the case for the oxime. With the assumption that the ring to be an undistorted inverting chair cyclohexane, the γ-hydrogens interconvert between the two locations (0°, 0°) and 0°, 120°). The spin density was calculated as the average of the values obtained for these two angles. In this manner, the ratio of the calculated spin densities in acetone oxime and cyclohexanone oxime was $-1.48{:}-1.43$ for the trans protons and, on the same scale, $-2.25{:}-1.8$ for the cis protons. However, as noted above these latter values must be expected to be the negative extremes for these protons.

In making absolute assignments for cyclohexanone oxime it was assumed that the ratios of the Q values in this and in acetone oxime parallel the calculated spin densities. However, since it is necessary to have only one reference for each molecule and since there is evidence for the unreliability of the values calculated for the cis protons, we have assigned the trans methylene protons in cyclohexanone oxime the value of -34.3 in accord with the ratio mentioned above.

In the NMR spectrum of cyclohexanone oxime the resonances of the protons bonded to C-2 and C-6 are readily distinguished, the downfield absorptions having previously been assigned to those trans to the lone pair.[49] The remaining protons do not give rise to separate resonances at 60 MHz, but on adding $Ni(acac)_2$ relative spin densities $-0.8{:}-1.00{:}+0.32{:}0{:}0$ could be determined. Of these, the first two values clearly are for the protons at C-2 and C-6, respectively, and the assigned shifts are then shown in **13**.



13

The remaining nonzero value was assigned in accordance with the W-plan rule. The similarity between the values for the C-2 and C-6 methylene protons in this oxime and the corresponding values for the protons in 2-butanone oxime tends to suggest that the use of the INDO calculations has not introduced any substantial error into this analysis.

Numerous substituted cyclohexanone iminoxy radicals have been studied by Russell and Mackor,[50] and they report ESR hfsc's of 1.4 G for the four γ and two δ protons. These values are the

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(47) G. R. Underwood, V. L. Vogel, and J. M. Iorio, *Mol. Phys.*, **25**, 1093 (1973).

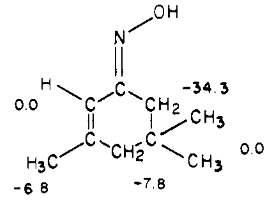
(48) Y. Ellinger, A. Rassat, R. Subra, and G. Bertier, *J. Am. Chem. Soc.*, **95**, 2372 (1973).

(49) (a) W. F. Trager and A. C. Hultric, *Tetrahedron Lett.*, 825 (1966); (b) H. Saito, K. Nukada, and M. Ohno, *ibid.*, 2124 (1964).

(50) G. A. Russell and A. Mackor, *J. Am. Chem. Soc.*, **96**, 145 (1974).

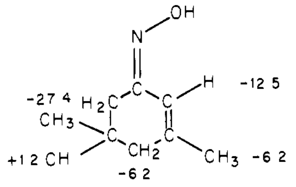
same as had been reported for the acetone iminoxy radical[4] and in view of the fact that the ESR linewidths remained of the order of 0.5G, presumably due to small residual long range coupling, these results show quite satisfactory agreement with our own.

Isophorone Oxime. Both isomers of this oxime can be isolated directly from the reaction mixture, by either crystallization or chromatography. That isomer, **14**, with the hydroxyl group away from the double bond (assigned on the basis that the vinylic proton showed an upfield shift of 0.3 ppm relative to that of its diastereomer) showed resonances at δ 2.41, 1.98, 1.85, and 0.99 assigned, respectively, to the vinylic, α-CH$_2$, γ-CH$_2$, C-3 methyl, and C-5 *gem*-dimethyl protons. Taking the C-6 methylene protons as having the same Q value as those in the (somewhat more flexible) cyclohexanone oxime led to the relative induced shifts. The appearance of little spin at the vinylic proton ($\theta_{\beta}{}^{c} = 0^\circ$, $\theta_{\gamma}{}^{H} = 0^\circ$) confirms our reluctance to use INDO-calculated spin densities in this region but is in excellent accord with ab initio calculations and other experimental data on molecules possessing similar structural fragments.



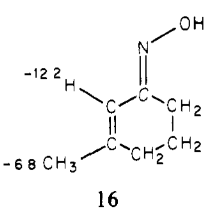
14

The other isomer, **15**, of this oxime obtained after column chromatography of the approximately 60:40 mixture showed ^{1}H NMR resonances at δ 2.1, 1.98, 1.85, and 0.99 assigned respectively to the α-CH$_2$, γ-CH$_2$, C-3 methyl, and C-5 *gem*-dimethyl protons. Again taking the α-CH$_2$ protons to have contact shifts similar to those in cyclohexanone, the relative spin densities obtained were shown in **15**. The close similarity between the shifts for the protons bonded to C-4 and C-7 in this isomer and its diastereomer suggests little dependence of the spin densities at these mobile hydrogens on the orientation of the nitrogen lone pair. The value of −12.5 for the vinylic proton also is in satisfactory agreement with the INDO calculations.

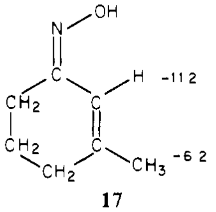


15

3-Methylcyclohexenone. The ^{1}H NMR spectrum of this oxime shows the apparent existence of only one isomer. The chemical shift of the vinylic proton is not particularly useful in aiding in the assignment as its value (δ 6.68) is intermediate between those of the corresponding protons of the isophorone oximes, nor are the methylene protons readily distinguished in the absence or presence of Ni(acac)$_2$. The only two shifts which can be readily identified are the methyl and vinyl hydrogen. Taking the methyl hydrogens to have an induced shift equal to that in the corresponding derivative of isophorone leads to Q values of those shown in either **16** or **17**. Of these we clearly favor the latter assignment.



16



17

Cyclohexadienone and Adamantanone Oximes. In making the Q value assignments so far, we haver relied heavily on the assumption that similarly located hydrogens have the same value. Using the results for acetone oxime (above), we were able to show that the errors introduced by this assumption were small for the acyclic oximes. In the cyclic ketones we have just discussed, however, we were particularly concerned by the possible errors introduced in this way since not only did the molecules undoubtedly have differing degrees of flexibility, but the delocalization pathways include carbons of different hybridizations. In the α,β-unsaturated ketoximes we arrived at Q values for protons located in the (0°, 0°) and (180°, 0°) regions using the independent evolutionary sequences shown in Figure 4. We can now check the mutual consistency of these results by examining molecules in which both geometries occur together. Such molecules are adamantanone and cyclohexadienone oximes.

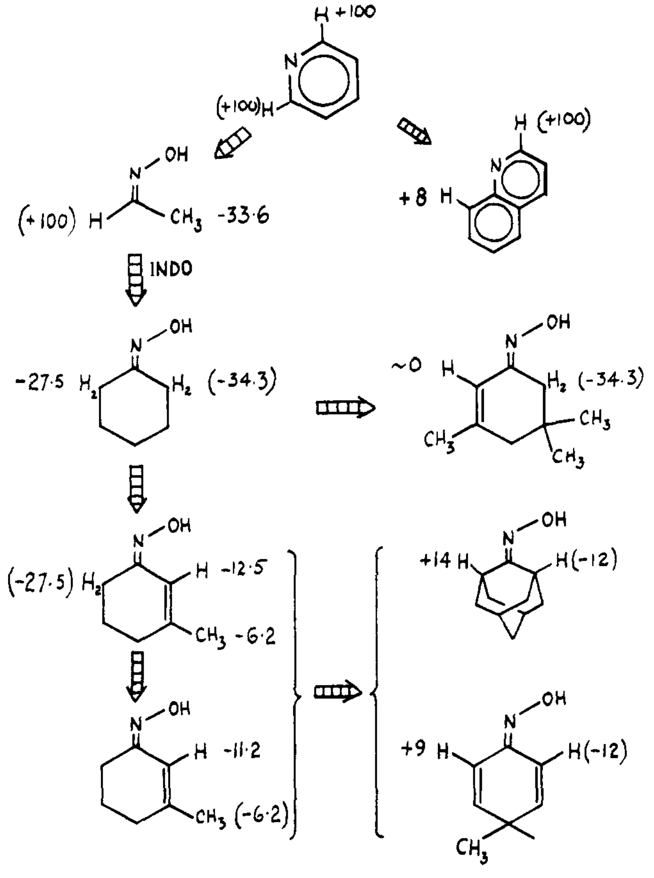
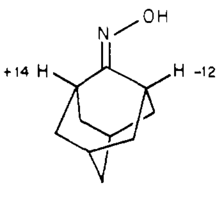


Figure 4. The particular sequence of assumptions used in arriving at the value for the induced proton shifts for the adamantanone and cyclohexadienone oximes. The reasonable agreement between the two positive values (+9 and +14) suggests little dependence upon hybridization, and their similarity to that for H-8 of quinoline (+8) supports the assumptions used.

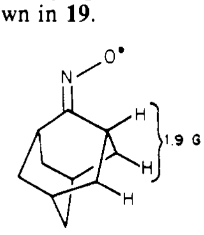
The NMR spectrum of adamantanone oxime shows resonances at δ 3.59 (1 H) and 2.68 (1 H) attributable to the two relevant methine protons. The former of these resonances is assigned to the proton trans to the lone pair (H-2). The induced shifts for these two protons (H-2/H-6) are in the ratio (−0.85/+1.00), and placing these on a common scale with the other oximes by using a value of −12 for the trans-methine hydrogen yields the values given in **18**.



18

The remaining 12 protons (seven magnetically distinct sets) all give rise to absorption between δ 1.7 and δ 2.2. On addition of Ni(acac)$_2$ this absorption broadened but it was not possible to identify positively any of the resonances.

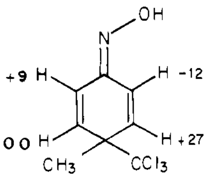
The iminoxy radical of adamantanone has been reported[50,51] to have three approximately equivalent hyperfine splittings which were assigned as shown in **19**.



19

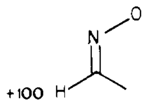
These assignments are clearly different from our own though it is emphasized that the complexity of the NMR spectra is not incompatible with the presence of substantial spin at these δ protons. Moreover, the induced shifts observed in other molecules possessing a similar structural fragment are positive and of a magnitude comparable with those obtained for these δ protons (see below) so we should expect that these δ protons would also have appreciable positive spin density. On the other hand, the resolution of the ESR experiment could preclude the observation of even a relatively large hfsc from H-6.

The NMR spectrum of the cyclohexadienone oxime[19] showed two resonances in the olefinic region at δ 6.45 and 7.20 having relative areas of 3:1. The downfield absorption was assigned to H-2. Upon adding Ni(acac)$_2$ the resonances separated and the contact shift assignments could be made as shown in **20**. The close agreement between the two values for the cis γ protons in these two molecules is substantial testament to the fact that the spin densities are determined overwhelmingly by the partial structural geometries relating that proton to the lone pair and are almost entirely independent even of the extreme perturbation of changing the hybridization of the adjacent carbons from sp^2 to sp^3. These values are both more positive than calculated by the INDO method and more positive than the values determined experimentally for isophorone, cyclohexenone, and 3-methylcyclohexenone. With respect to the calculated value, this is not surprising and it is reassuring that Elligner et al.,[48] who appear to have carried out the most reliable spin density calculations on a radical with a similar structure to this fragment, obtained a small positive spin density for this conformation. On the other hand the oxime **14** is more flexible than are the cyclohexadienone or adamantanone oximes, and, since the (0°, 0°) geometry corresponds to a maximum on the curve in Figure 3, any oscillation about this point would serve to make more negative the spin density at that proton.



20

Comparison with Other Contact Shift Data. The evolution of these results has been in such a manner as to suggest that the majority of the spin has been induced in the nitrogen nonbonding orbital with little to be gained by a consideration of spin delocalized to oxygen. This is supported by the fact that best agreement was found between experimental spin densities and those calculated for the α-hydroxy vinyl radical in which less than 10% of the spin was delocalized to oxygen. It is also underscored by comparing these results with data obtained in pyridines and polycyclic amines containing the same structural fragments but from which the oximino linkage is absent. In making these comparisons the two reference values were



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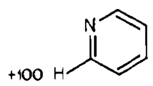
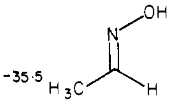
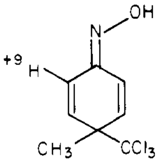
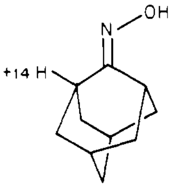
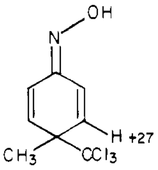


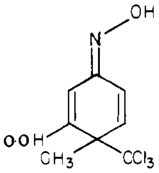
The former leads to the assignments, based on the assumptions outlined above











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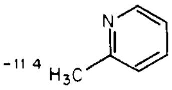

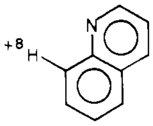

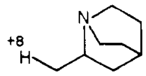

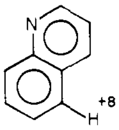

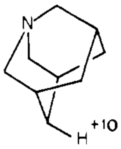

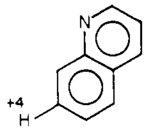

The most satisfactory correspondence between these data for such widely differing compounds strongly supports the suggestion that spin delocalization in these systems is largely independent of all but those bonds directly linking the radical site to the proton in question. It also justifies the technique of equating Q vlaues for similar protons in different molecules. Furthermore, it appears that little is to be gained by considering any effect due to spin delocalized onto oxygen.

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Registry No. 2a, 75-17-2; **7a**, 10341-59-0; **7b**, 10341-63-6; **13**, 100-64-1; **14**, 81294-19-1; **15**, 81294-20-4; **17**, 1610-01-1; **18**, 4500-12-3; **20**, 81294-21-5; *syn*-acetaldoxime, 5775-72-4; *anti*-acetaldoxime, 5780-37-0; acetone oxime, 127-06-0.

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(51) H. Caldararu and M. Moraru, *J. Am. Chem. Soc.*, **96**, 149 (1974).