Carbon-13 Chemical Shifts of the Carbonyl Group. 8. Approximate Self-Consistent-Field Perturbation Theory

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Abstract: The previously reported SCF perturbation theory of ^{13}C chemical shifts at the modified INDO level has been extended to oxygen-containing compounds. A promising level of qualitative agreement has been observed between calculated and experimental trends among alcohols, aldehydes, ketones, carboxylic acids, and their corresponding isoelectronic hydrocarbons. Relationships between computed electron density elements and ^{13}C shifts are explored, but only limited correlations are found. The modified INDO parameters chosen for oxygen tend to exaggerate the degree of electronic polarizations associated with oxygen in organic compounds. The role of intermolecular interactions, mainly hydrogen bonding, is explored by means of calculations on configurations that model suspected interactions.

Introduction

Oxygen-containing organic compounds have played an important role in the development of ^{13}C NMR, a field that has enjoyed a great surge of interest and activity during the past few years. Carbonyl compounds have been subjects of intensive ^{13}C NMR study in this[1] and other laboratories.[2] The carbonyl and hydroxyl functional groups figure importantly in a wide range of chemical problems to which ^{13}C NMR is being applied, including many that are biologically oriented. The proper interpretation of ^{13}C chemical shifts is an important prerequisite to the most efficient utilization of the ^{13}C NMR technique in a wide variety of applications. The availability of a dependable ^{13}C chemical shift theory, especially if it is computationally realistic, can provide a valuable framework for the interpretation of experimental data and useful guidelines for the design of experiments.

Although most applications of the ^{13}C chemical shift parameter in experimental problems are largely of an empirical nature, it is generally assumed that this shift parameter has the potential of providing valuable information about electronic distributions in molecules. Indeed, it is not uncommon to find statements in the literature which imply that such information can be extracted directly and simply from experimental data, e.g., by the *assumption* of simple linear relationships between chemical shifts and atomic or π orbital electron densities. However, in our judgement, such assumptions are in many cases rather gross oversimplifications of reality; and, while they may be qualitatively valid in some types of systems, they have seldom been based on careful scientific justification.

Although early theoretical developments of ^{13}C shielding provided extremely valuable insights and qualitative guideposts for an emerging field, only recently have *computationally* promising theories of ^{13}C chemical shifts appeared. Ditchfield, Miller, and Pople[3] in 1970 presented an ab initio SCF-MO perturbation theory of ^{13}C shielding. Although promising results were obtained, they were not gauge invariant. More recently Ditchfield[4,5] has reported an impressive set of results based on an ab initio approach employing gauge-invariant Slater atomic orbitals as a basis set. In 1972 Ellis, Maciel, and McIver[6] reported results obtained by SCF-MO perturbation calculations on hydrocarbons at the INDO level of approximation,[7] using gauge-invariant atomic orbitals and a finite perturbation method. This approach has more recently been employed in an attempt to account for the "electronegativity effect" of substituents on ^{13}C chemical shifts,[8] and has been extended in sophistication somewhat by Ellis.[9] The present paper is concerned with applying the same approach to oxygen-containing organic systems, with emphasis on the carbonyl group. The primary aim of this work was to extend the qualitatively successful INDO perturbation theory of ^{13}C chemical shifts of hydrocarbons to oxygen-containing cases. The immediate value associated with this goal is to have a computationally fast theory, having a reasonable enough level of agreement with experimental data so that detailed examination of the computed results can provide chemical insights and/or conclusions that are currently not available in ^{13}C NMR studies.

Results and Discussion

1. Approximate SCF-MO Perturbation Method. The calculations were carried out at the INDO level,[7] as reported earlier by Ellis, Maciel, and McIver,[6] using the equation

$$\sigma_{\alpha\beta}(\mathrm{M}) = \sigma_{\alpha\beta}{}^{\mathrm{d}}(\mathrm{M,M}) + \sigma_{\alpha\beta}{}^{\mathrm{p}}(\mathrm{M,M}) + \sum_{\mathrm{K}\neq\mathrm{M}}^{\mathrm{atoms}} [\sigma_{\alpha\beta}{}^{\mathrm{d}}(\mathrm{M,K}) + \sigma_{\alpha\beta}{}^{\mathrm{p}}(\mathrm{M,K})] \quad (1)$$

In this equation, $\sigma_{\alpha\beta}(\mathrm{M})$ is the $\alpha\beta$ element (α or $\beta = x, y,$ or z) of the shielding tensor for nucleus M; $\sigma_{\alpha\beta}{}^{\mathrm{d}}(\mathrm{M,M})$ and $\sigma_{\alpha\beta}{}^{\mathrm{p}}(\mathrm{M,M})$ are the local diamagnetic and paramagnetic contributions, respectively, to that element of the tensor; and $\sigma_{\alpha\beta}{}^{\mathrm{d}}(\mathrm{M,K})$ and $\sigma_{\alpha\beta}{}^{\mathrm{p}}(\mathrm{M,K})$ represent the contributions to that tensor element due to diamagnetic and paramagnetic currents on the *K*th other atom. The two center terms, $\sigma_{\alpha\beta}{}^{\mathrm{d}}(\mathrm{M,K})$ and $\sigma_{\alpha\beta}{}^{\mathrm{p}}(\mathrm{M,K})$, were computed using the long-range approximation given by McConnell and Pople.[10] The one-center contributions of eq 1 were calculated according to eq 2 and 3, given by Ellis, Maciel, and McIver.[6]

$$\sigma_{\alpha\beta}{}^{\mathrm{d}}(\mathrm{M,M}) = 2\sum_{\mu}^{\mathrm{M}}\sum_{\nu}^{\mathrm{M}} R_{\mu\nu}(0)\langle X_\mu{}^0|h_{\alpha\beta}{}^{11}(\mathrm{M})|X_\nu{}^0\rangle \quad (2)$$

$$\sigma_{\alpha\beta}{}^{\mathrm{p}}(\mathrm{M,M}) = 2\sum_{\mu}^{\mathrm{M}}\sum_{\nu}^{\mathrm{M}} \left(\frac{\partial R_{\mu\nu}}{\partial B_\alpha}\right)_0 \langle X_\mu{}^0|h_\beta{}^{10}(\mathrm{M})|X_\nu{}^0\rangle \quad (3)$$

In eq 2 and 3, $R_{\mu\nu}(0)$ is the value of the $\mu\nu$ element of the density matrix (**R**) in the absence of a perturbation; the definitions of the operators $h_{\alpha\beta}{}^{11}(\mathrm{M})$ and $h_\beta{}^{10}(\mathrm{M})$ have been given previously, according to eq 4 and 5.[6] B_α is the $x, y,$ or z component of the applied magnetic field strength.

$$h_{\alpha\beta}{}^{11}(\mathrm{M}) = \frac{e^2}{2mc^2}(\mathbf{r}_\nu\mathbf{r}_{\mathrm{M}}\delta_{\alpha\beta} - \mathbf{r}_{\nu\alpha}\mathbf{r}_{\mathrm{M}\beta})/|\mathbf{r}_{\mathrm{M}}|^3 \quad (4)$$

$$h_\beta{}^{10}(\mathrm{M}) = \frac{eh}{mci}\frac{(\mathbf{r}_{\mathrm{M}} \times \nabla)_\beta}{|\mathbf{r}_{\mathrm{M}}|^3} \quad (5)$$

As in the previously reported work based on this method,[6,7] Slater's screening rules[11] were used in the evaluations of integrals of the types $\langle r^{-3}\rangle$ and $\langle r^{-1}\rangle$; this is a simple, albeit

Table I. Atomic INDO Parameters Used in Standard INDO Calculations and Those Used in ^{13}C Chemical Shift Calculations Reported Here[a]

Atom	Standard INDO parameters[b]				Modified INDO parameters[c]			
	$\frac{1}{2}(I+A)_s$	$\frac{1}{2}(I+A)_p$	β_0	ξ	$\frac{1}{2}(I+A)_s$	$\frac{1}{2}(I+A)_p$	β_0	ξ
Hydrogen	7.176		−9.0	1.2	7.176		−12.0	1.2
Carbon	14.051	5.572	−21.0	1.625	17.051	8.572	−17.0	1.625
Oxygen	25.390	9.111	−31.0	2.275	30.0	13.5	−24.0	2.175

[a] Units are eV, except for Slater exponents. [b] Parameters taken from ref 7. [c] Parameters used in ^{13}C chemical shift calculations reported here.

imperfect, way of attempting to take into account the effects of the different environments of nonequivalent carbon atoms on these types of integrals. In the INDO framework, this simple approach takes the form of the equation

$$\xi = [3.25 - 0.35(P - 4)]/2 \qquad (6)$$

where ξ is the Slater exponent involved in the computation of the integrals and P stands for the total valence-shell electron density of the carbon in question.[6] As in the previous work, the London overlap approximation[12] was employed, and the same set of modified atomic INDO parameters for carbon and hydrogen were employed in this work. The standard geometrical model of Pople and Gordon[13] was employed for all monomers or dimer components.

2. Modified INDO Parameters for Oxygen. The first essential task of the project was to determine if a suitable set of oxygen parameters for the modified INDO framework could be found. Unsatisfactory results are obtained in this approach if standard INDO parameters are employed. The criteria were that reasonable qualitative agreement be established between computed and experimental ^{13}C chemical shifts, and that qualitatively reasonable alterations of computed electronic distribution be associated with specific alterations in structure; the basis of both criteria was the following set of test compounds: CH_3OH, CH_3CH_2OH, CH_3CHO, HCO_2H, CH_3CO_2H, and C_6H_5OH. The criteria of reasonable patterns of electronic distributions was based upon comparison with a more conventional approximate MO method, CNDO/2.[14]

Calculations on certain other oxygen-containing species were also carried out, e.g., CO, CO_2, H_2CO, CH_3CO^+, and some anions. These species were not included in the consideration of oxygen parameter sets for the following reasons. It was desired to optimize the parameterization with respect to molecules containing C, H, and O in structural situations that are representative of typical classes of neutral organic molecules of wide interest in experimental work. The neutral species CO, CO_2, and H_2CO, while of some interest theoretically, are each unique in structural type, and not representative of entire classes of organic molecules in the same sense as are the species listed above. Cationic and anionic species were excluded from consideration in the parameterization step because it was anticipated that there might be special difficulty in obtaining the same level of agreement for ionic species as for neutral species, and we wished to weigh the parameterization on the side of neutrals. These ionic and unique cases are discussed in more detail below.

An extensive series of calculations was performed with a variety of sets of oxygen INDO parameters on the structures CH_3OH, CH_3CH_2OH, CH_3CHO, and HCO_2H; CH_3CO_2H and C_6H_5OH were excluded from these trial calculations in order to conserve computer time. The most promising sets of oxygen INDO parameters, on the basis of the above mentioned two criteria, were also employed in calculations on CH_3CO_2H and C_6H_5OH and, on the basis of results for all six compounds, a particular parameter set was then chosen for the remainder of the work reported in this paper. It cannot be claimed that the oxygen INDO parameter set chosen in this manner is "optimized" in a systematic statistical sense, and it is likely that better results could be obtained by a systematic optimization of not only the oxygen parameters, but also the carbon and hydrogen parameters, for compounds containing carbon, hydrogen, and oxygen. However, a complete parameterization of this type would require a great deal of computer time and the set chosen for the work appears to be suitable for the present purposes, i.e., accounting for the major features of oxygen effects on ^{13}C chemical shifts, especially for carbonyl compounds. Table I gives the oxygen INDO parameters chosen, together with the previously determined carbon and hydrogen parameters and the standard INDO carbon, hydrogen, and oxygen parameters. It should be emphasized here that the attention in this work was focussed entirely on ^{13}C chemical shifts. Although some gross patterns of experimental ^{17}O shifts appeared to be roughly accounted for in these calculations, the emphasis in choosing the parameters and assessing the results was completely on ^{13}C shifts.

An additional important point is that we do *not* suggest that these modified carbon, hydrogen, and oxygen parameters generally replace the "standard" values in routine INDO calculations carried out for other purposes, e.g., for energies or electron distributions. The parameter set employed in this work is recommended only for the specific types of calculations reported here. It seems likely that the natural evolution of ^{13}C chemical shift theory will provide improved theoretical frameworks, for which other atomic parameters will be more desirable.

The ^{13}C chemical shifts computed for the set of test compounds are given in Table II, together with the calculated shifts of the corresponding isoelectronic hydrocarbons (i.e., replacing OH with CH_3 and/or C=O with $C{=}CH_2$). The corresponding experimental data are also given in the table.

Table II also includes information on the computed density matrices, which represent atomic and orbital electron densities in the INDO MO framework. The electron densities summarized in Table II served, as mentioned above, as one of the criteria for choosing the oxygen parameter set, the guideposts being the corresponding electron densities calculated by the CNDO/2 method. While it is not claimed that CNDO/2 provides truly accurate wave functions, the density matrices computed by this method have proved to be qualitatively successful in reproducing the main features of ab initio calculations.

The modified INDO perturbation theory has previously been assessed for its ability and limitations in representing structural effects in hydrocarbons,[6] e.g., the effect of replacing a hydrogen atom in methane by a methyl group or a phenyl group. In assessing the validity of these calculations on oxygen-containing compounds, attention is focused explicitly upon the "oxygen effect", i.e., the change in a computed quantity associated with the introduction of oxygen into the molecular framework of interest. We have chosen to view this as the difference between a quantity computed for the oxygen-containing molecule of interest and the corresponding quantity computed for the isoelectronic hydrocarbon, e.g., δ_c for CH_3OH minus δ_c for CH_3CH_3. Table III summarizes such oxygen effects upon pertinent measures of the electron distributions in the molecules of Table II, computed by the

Table II. ^{13}C Chemical Shifts and Electron Density Elements Calculated by the Modified INDO Perturbation Method for Representative C, H, and O Molecules

Molecule	Calcd shift[a] $\delta C(1)$ ($\delta C(2)$)	Exptl shift[b] $\delta C(1)$ ($\delta C(2)$)	Calculated valence-shell atom or orbital electron density[c] $P_{C(1)}$ ($P_{C(2)}$)	$P_{\pi 1}$ ($P_{\pi 2}$)	$P_{\sigma 1}$ ($P_{\sigma 2}$)	$P_{C,H}$	$P_{O(2)H}$	P_O	$P_{O\pi}$	$P_{O\sigma}$
CH_3OH	19.5	51.4[h]	4.048	1.076	2.972	0.917		6.518	1.986	4.532
CH_3CH_3	3.0	8.0[i,j]	4.274	1.083	3.191	0.909				
$C^2H_3C^1H_2OH$	21.3	59.4[h]	3.868	1.014	2.854	0.885	0.949	6.550	1.985	4.565
	(4.6)	(20.0)	(4.342)							
$C^2H_3C^1H_2CH_3$[d]	2.8	19.9[i,j]	4.088	1.008	3.080	0.935	0.905			
	(6.5)	(19.5)	(4.308)							
$C^2H_3C^1H{=}O$[e]	192.4	201.7[k,l]	3.633	0.693	2.940	0.955	0.854	6.448	1.360	5.088
	(9.7)	(33.3)	(4.401)	(1.121)	(3.280)					
$C^2H_3C^1{=}CH_2$	126.3	138.3[m]	4.006	0.950	3.056	0.929	0.892			
	(6.0)	(20.8)[n]	(4.317)	(1.088)	(3.229)					
$HC({=}O^1)O^2H$	193.1	168.8[o,l]	3.420	0.682	2.738	0.930		6.482	1.439	5.043
								(6.541)	(1.879)	(4.662)
$C^2H_3C^1({=}O^1)O^2H$	190.3	179.4[o,p,q]	3.286	0.653	2.633		0.835	6.551	1.508	5.043
	(8.2)	(23.2)[l]	(4.444)	(1.135)	(3.309)			(6.579)	(1.890)	(4.689)
$C^2H_3C^1({=}O)CH_3$	186.7	207.2[p]	3.489	0.665	2.824		0.855	6.513	1.431	5.082
	(10.0)	(32.3)[k,l]	(4.434)	(1.116)	(3.318)					
$C^2H_3C^1({=}CH_2)CH_3$	134.8	143.3[r]	3.827	0.903	2.924		0.886			
	(7.2)	(25.4)[r]	(4.356)	(1.098)	(3.258)					
C_6H_5OH[f] (1)	139.3	157.7[s]	3.668	0.922	2.746			6.546	1.935	4.611
(2)	118.5	118.2	4.199	1.079	3.120		0.894[g]			
(3)	125.6	132.6	4.034	0.969	3.065		0.918[g]			
(4)	120.4	122.9	4.120	1.045	3.075		0.913[g]			
$C_6H_5CH_3$[f]	129.8	139.0[t]	3.896	0.943	4.138					
	120.8	130.5	4.138	1.041	3.097		0.914[g]			
	122.4	129.7	4.061	0.985	3.076		0.924[g]			
	120.3	126.8	4.102	1.027	3.075		0.921[g]			

[a] Calculated from eq 1–5, parts per million relative to methane. Larger values correspond to lower shielding. The results for all the hydrocarbons, except 2-methylpropene, were taken from ref 6; the 2-methylpropene results and those of all the oxygen-containing species were obtained in this work. Value in parentheses below is for C(2). Average values are given where appropriate. [b] Parts per million with respect to methane. Literature references indicated in parentheses. Value in parentheses below is for C(2). [c] Valence-shell atomic density $P = P_{2s2s} + P_{p_xp_x} + P_{p_yp_y} + P_{p_zp_z}$ for that atom. $P_\pi = P_{p_yp_y}$, i.e., the carbon π orbital is taken to be $2p_y$, where the xz plane is designated as the plane of symmetry of the molecule, where appropriate, as defined in the text. The σ-electron density is the total atomic density minus the π-orbital density. Average values are given where appropriate, Values below in parentheses are for C(2) or O(2), as numbered. [d] The calculation was carried out for a conformation with a trans-planar H–C–C–H arrangement in the xz plane. [e] The calculation was carried out for a conformation with a trans-planar H–C–C–O arrangement in the xz plane. [f] Carbon position designations (1)–(4) for these molecules correspond to carbons 1-4, respectively. [g] The three numbers represent ortho, meta, and para hydrogens, in that order. [h] J. D. Roberts, F. J. Weigert, J. I. Kroschwitz, and H. J. Reich, *J. Am. Chem. Soc.*, 92, 1338 (1970). [i] H. Spiesecke and W. G. Schneider, *J. Chem. Phys.*, 35, 722 (1961). [j] D. M. Grant and E. G. Paul, *J. Am. Chem. Soc.*, 86, 2984 (1964). [k] L. M. Jackman and D. P. Kelley, *J. Chem. Soc. B*, 102 (1970). [l] J. B. Stothers and P. C. Lauterbur, *Can. J. Chem.*, 42, 1563 (1964). [m] G. B. Savitsky, P. D. Ellis, K. Namikawa, and G. E. Maciel, *J. Chem. Phys.*, 49, 2395 (1968). [n] A. J. Jones and D. M. Grant as reported in "Carbon-13 NMR Spectroscopy", J. B. Stothers, Ed., Academic Press, New York, N.Y., 1972, p 81. [o] R. Hagen and J. D. Roberts, *J. Am. Chem. Soc.*, 91, 4504 (1969). [p] G. A. Gray, P. D. Ellis, D. D. Traficante, and G. E. Maciel, *J. Magn. Resn.*, 1, 41 (1969). [q] G. E. Maciel and D. D. Traficante, *J. Am. Chem. Soc.*, 88, 220 (1966). [r] Footnote *n*, p 82. [s] G. E. Maciel and J. J. Natterstad, *J. Chem. Phys.*, 42, 2427 (1965). [t] D. Lauer, E. L. Motell, D. D. Traficante, and G. E. Maciel, *J. Am. Chem. Soc.*, 94, 5335 (1972).

Table III. Calculated "Oxygen Effects" on Electronic Distributions[a] of Representative C, H, and O Molecules

	INDO perturbation theory								CNDO/2							
Molecule	$\Delta P_{C(1)}$	ΔP_{π_1}	ΔP_{σ_1}	$\Delta P_{C(2)}$	ΔP_{π_2}	ΔP_{σ_2}	ΔP_{H_1}	ΔP_{H_2}	$\Delta P_{C(1)}$	ΔP_{π_1}	ΔP_{σ_1}	$\Delta P_{C(2)}$	ΔP_{π_2}	ΔP_{σ_2}	ΔP_{H_1}	ΔP_{H_2}
C^1H_3OH	−226	−7	−219				8		−136	−3	−133				10	
$C^2H_3C^1H_2OH$	−220	6	−226	34			−53	58	−113	3	−116	26	4	22	−18	23
CH_3COCH_3	−338	−238	−100	78	18	60		−31	−201	−127	−74	54	7	47		−21
$C^2H_3C^1HO$	−373	−257	−116	84	33	51	26	−37	−220	−144	−76	56	17	39	35	−46
HCO_2H	−586	−268	−318				1		−353	−167	−186				16	
$C^2H_3C^1O_2H$	−541	−250	−291	88	37	51		−51	−335	−153	−182	68	22	46		−33
C_6H_5OH[b]	−228	−21	−207	61	38	23		−20[c]	−143	−26	−117	44	42	2		−12[c]
	−27	−16	−11	18	18	0		−6	−17	−16	−1	19	27	−8		−2
								−8								−1

[a] ΔP_i stands for the calculated electron density of the *i*th atom, or the *i*th σ or π atomic orbital, in an oxygen-substituted hydrocarbon minus the electron density in the corresponding isoelectronic hydrocarbon. Molecular conformations and σ, π specifications are given in Table II. Values given are actual values times 1000. [b] Position designations: in second row, designations for carbons 1 and 2 refer to carbons 3 and 4, respectively. [c] The three numbers represent ortho, meta, para hydrogens, in that order.

modified INDO calculation and CNDO/2. In this table the electron distributions are partitioned between a σ framework (composed with atomic orbitals with axes in the plane containing the carbon atom to which oxygen is attached and two additional atoms attached to the C–O moiety) and a π framework (composed of atomic orbitals with nodes in that plane). In comparing the modified INDO results and the CNDO/2 results in Table III, it is seen that there is a very strong qualitative correspondence between the oxygen effects computed by these two approaches. For example, if one compares ΔP, ΔP_π, and ΔP_σ for any particular carbon atom or pair of carbon atoms in a molecule, except for one minor discrepancy in the phenol case, corresponding quantities have the same signs and even follow the same algebraic orders in the two MO frameworks; the same is true of ΔP_H values. As in an earlier study in which fluorine was incorporated into the modified INDO perturbation theory of ^{13}C chemical shifts,[8] it was found here that, in order to achieve satisfactory qualitative agreement with experimental ^{13}C data, modified (oxygen) INDO parameters are needed that lead to generally larger polarizations in calculated electronic distributions than one computes by CNDO/2 or standard INDO methods. Nevertheless, we conclude that the major features of oxygen effects in density matrix elements calculated by CNDO/2 are present in the density matrix obtained by an INDO approach that is modified as indicated in Table I.

Examination of the chemical shift results in Table II shows very promising patterns of agreement between calculated and experimental results. Viewing the results in methyl and ethyl alcohols, either relative to methane or with respect to the corresponding isoelectronic hydrocarbon (ethane and propane), shows a large decrease in shielding at the α carbon and a small shift to smaller shielding at the β carbon in ethanol (the experimental β effect is experimentally essentially zero if propane is the reference, but is negative if ethane or methane is considered a reference). The rather low shielding values typical of a carbonyl group are qualitatively accounted for by the results on acetaldehyde, acetone, and the two carboxylic acids. Viewed in terms of "oxygen effects", as described above, one sees that the substitution of $^*C{=}O$ for $^*C{=}CH_2$ in constructing acetaldehyde and acetone leads to a decrease in C* shielding of about 60–80 ppm, both theoretically and experimentally. Comparing formic acid and acetic acid with their corresponding isoelectronic hydrocarbons (propene and 2-butene, respectively), one sees that the experimental increment of about 32 ppm is computed to be about 60 ppm. Thus, the carbonyl carbon shifts, while computed to be in qualitatively the correct general region, correspond to computed oxygen effects that are exaggerated. A large part of that exaggeration, however, about 10 ppm, is due to computed shieldings of the corresponding olefinic carbons that are too large.

If one lists the chemical shifts of the methyl groups in the oxygen containing molecules represented in Table II in decreasing order of shielding, one finds that the computed order is precisely the same as that of the experimental order. In fact, if the corresponding hydrocarbons in Table II are included in the list, only two minor permutations are required to place all of the computed methyl shifts in the correct experimental order. The range of the computed methyl shifts is much smaller than the experimentally determined range, and a computed shift (from methane) invariably is smaller than the corresponding experimental value.

Table IV. Role of Slater Exponent Corrections in Calculation of "Oxygen Effects" on ^{13}C Chemical Shifts[a]

	Calculated without Slater correction[b]		Calculated with Slater correction[c]		Exptl[d]	
Molecule	$\Delta\delta_{C_1}$	$\Delta\delta_{C_2}$	$\Delta\delta_{C_1}$	$\Delta\delta_{C_2}$	$\Delta\delta_{C_1}$	$\Delta\delta_{C_2}$
CH_3OH	13.8		16.5		43.4	
$C^2H_3C^1H_2OH$	8.2	5.5	18.5	−1.9	41.2	2.3
CH_3COCH_3	29.1	4.7	51.9	3.1	62.9	6.9
$C^2H_3C^1H{=}O$	41.6	5.6	66.1	3.5	67.4	10.7
HCO_2H	30.3		66.9		33.6	
CH_3CO_2H	21.9	2.6	50.9	0.8	36.1	−2.2
C_6H_5OH[e]	−2.0	−0.1	9.5	−3.0	18.7	−12.3
	0.9	1.1	2.4	0.1	2.9	−3.9

[a] $-\Delta\delta_C$ represents the shielding of the *i*th carbon of an oxygen-containing compound minus the shielding of the corresponding carbon in the isoelectronic hydrocarbon. [b] Calculated without using eq 6. [c] Calculated with correction embodied in eq 6 included, i.e., corresponding to the results in Table II. [d] Experimental data referenced in Table II. [e] Carbon position designations: for second row, carbons 1 and 2 refer to carbons 3 and 4, respectively.

Phenol is the only neutral aromatic molecule to which this approach has been applied in this study. It is gratifying to note in Table II that the experimental order of the carbon shifts is retained in the calculated results. The computed "oxygen effects", with respect to toluene, are also in the experimentally correct algebraic order, although the para value is computed to be nearly zero, whereas the experimental value is −3.9. If viewed with respect to benzene rather than toluene, the computed OH substituent effects on ^{13}C shifts are also all in the correct algebraic order, and all of the correct signs. It is interesting to note that there are some very regular correlations between computed (or experimental) values of the ^{13}C chemical shifts of phenol and corresponding electron density elements computed in the chemical shift calculation. For example, it is found that the four ^{13}C shifts of phenol follow monotonically the computed total electron density at each carbon, or the π or σ portion of that total at each carbon. In the case of the calculated shifts and total carbon electron densities, the correlation is essentially linear. However, the linearity of this correlation is marred by inclusion of results on benzene and/or toluene; indeed, one of the toluene points destroys the monotonic character of the correlation. For the other correlations between shifts and electron density elements, the general quality of the correlation suffers by inclusion of toluene and benzene values, although the effect on the correlation between calculated shifts and π-electron densities is rather minor. It is also interesting that the computed or experimental "oxygen effects" (relative to toluene) on the ^{13}C shielding in phenol, which fall in the order $C(2) > C(4) > C(3) > C(1)$, are in the same order as the oxygen effects on the total π or σ electron densities computed in the chemical shift calculation, or, with one permutation, by CNDO/2.

The kinds of trends discussed here for the benzene framework of phenol are not found in general in the results summarized in Table II. Hence, linear or even monotonic correlations between ^{13}C chemical shifts and partial or total atomic electron densities appear to be limited to points within a rather narrow structural class.

3. Role of Slater Exponent Corrections. As indicated above, the results reported in this paper include a Slater exponent correction of the integrals $\langle r^{-3}\rangle$ and $\langle r^{-1}\rangle$, by means of the formula given in eq 6. In Table IV are summarized the oxygen effects on the chemical shifts (relative to isoelectronic hydrocarbons) calculated with and without this correction. It is seen that the Slater exponent correction gives small but significant improvements in $\Delta\delta_C$ for the carbon atoms of a simple alcohol. For the carbonyl carbon of acetaldehyde or acetone there is a dramatic improvement of the agreement of the computed results with experimental results, although the agreement of the oxygen effects on the methyl carbon shifts suffers somewhat. For the carboxyl carbons of formic and acetic acid, it is seen that inclusion of the Slater exponent correction exaggerates the oxygen effect, giving an effect of the correct sign, but considerably too large; the methyl carbon result for acetic acid is improved slightly by the correction.

For phenol, it is seen that inclusion of the Slater exponent correction is quite important. Without the correction, the experimentally determined order of the $\Delta\delta_C$ values is not obtained. Including the Slater correction not only places the $\Delta\delta_C$ values in the correct algebraic order, but also eliminates an otherwise incorrect sign of the value computed for the para position.

Table V. Chemical Shifts and Electron Density Elements of Unique C, H, and O Neutral Species Calculated by Modified INDO Perturbation Theory[a]

	Calcd shifts		Calcd electron density elements						Exptl shifts	
Molecule	δ_C	$\Delta\delta_C$	P_C	P_π	P_o	ΔP_C	ΔP_π	ΔP_σ	δ_C	$\Delta\delta_C$
CO	285.7	205.1	3.831	1.140	2.691	−322	−860	538	183.4[b]	107.4[b,d]
CO_2	227.8	45.1	3.160	1.330	1.830	−693	−444	−249	126.3[b]	−88.5[b,e]
H_2CO	195.2	80.1	3.799	0.729	3.070	−403	−271	−132	194.1[c]	68.7[c,f]

[a] Symbols defined in Tables II, III, and IV. [b] R. Ettinger, P. Blume, A. Patterson, Jr., and P. C. Lauterbur, *J. Chem. Phys.*, 33, 1597 (1960). [c] This work obtained at −30 °C in a 10% solution of cyclopentane ($\delta\,{}^1H$ = 8.00 rel to C_5H_{10} at −40 °C in 10% solution of C_5H_{10}). [d] R. M. Lynden-Bell and N. Sheppard, *Proc. R. Soc. London, Ser. A*, **269**, 385 (1962). [e] J. A. Pople, *Mol. Phys.*, 7, 301 (1964). [f] R. Ditchfield and P. D. Ellis, *Chem. Phys. Lett.*, 17, 342 (1972).

Table VI. Calculated ^{13}C Chemical Shifts and Electron Density Elements of Ions

	Calculated[a]		Experimental[b]			Calculated valence-shell atom or orbital electron density[c]									
Ion	δC(1)	δC(2)	δC(1)	δC(2)	Ref	$P_{C(1)}$	P_{π_1}	P_{σ_1}	$P_{C(2)}$	P_{π_2}	P_{σ_2}	P_H	$P_{O(1)}$	P_{π_0}	P_{σ_0}
CH_3O^-	38.7		57.1		*f*	4.135	1.960	2.175				1.012	6.930	3.960	2.970
HCO_2^-	252.0		173.8		*g*	3.473	0.661	2.812				1.071	6.728	1.670	5.058
$CH_3CO_2^-$	244.5	4.1	184.8	26.4	*g,h*	3.347	0.642	2.705	4.472	1.081	3.391	0.893[g]	6.752	1.698	5.054
$C_6H_5O^-$[d]	182.3	119.2	169.2	121.7	*i,j*	3.642	0.790	2.852	4.260	1.135	3.125	0.927[e]	6.780	1.814	4.966
												0.973			
	122.5	119.3	132.6	117.3		4.051	0.983	3.068	4.195	1.160	3.035	0.962			
CH_3CO^+	214.6	38.2	153.6	8.3	*h*	3.290	1.235	2.055	4.395	2.380	2.015	0.734	6.113	2.982	3.131
CO_3^{2-}	215.8		171.4		*k*	3.126	0.609	2.517					6.958	1.797	5.161

[a] Calculated from eq 1–5, parts per million relative to methane. Larger values correspond to lower shielding. Average values where appropriate. [b] Parts per million with respect to methane. [c] Symbols defined in Table II. [d] Position designations: see Table V. [e] Position designations: the values here refer to electron density at the hydrogen located at carbons 2, 3, and 4, respectively, from top to bottom. [f] Estimated from weighted average shift of a 7% CH_3O^- solution in CH_3OH. This work. [g] Determined relative to aqueous 1,4-dioxane. This work. [h] G. A. Gray, P. D. Ellis, D. D. Traficante, and G. E. Maciel, *J. Magn. Reson.*, 1, 41 (1969). [i] [a] G. E. Maciel and R. V. James, *J. Am. Chem. Soc.*, 86, 3893 (1964); [b] G. A. Gray, Ph.D. Thesis, University of California at Davis, 1967. [j] T. T. Nakashima and G. E. Maciel, *Appl. Spectrosc.*, 26, 220 (1972). [k] P. C. Lauterbur, *Phys. Rev. Lett.*, 1, 343 (1958).

The net result of including the Slater exponent correction is to introduce an explicit mechanism into the calculation for the influence of electronic polarizations within a given structural framework. Even without such a correction, the effect of carbon hybridization (coordination number) is included in the theory, along with some effects of electronic polarizations. The Slater exponent correction, which attempts to take into account the influence of orbital size, provides an additional explicit influence of electron polarization in the calculations.

4. Unique Neutral Species. Table V summarizes results on CO, CO_2, and H_2CO, neutral species that can legitimately be considered unique. For H_2CO it is seen that the computed shift relative to methane is nearly quantitatively correct, and the corresponding computed oxygen effect is qualitatively satisfactory (69 vs. 80 ppm). This level of agreement for H_2CO is not surprising in view of the heavy emphasis given to carbonyl-containing compounds in the parameterization. For the other two compounds in Table V the agreement with experiment is not as satisfactory, although some features of the experimental data are reproduced in the calculation. The experimental shift difference of about 58 ppm between CO and CO_2 is reproduced in the calculation, as well as the experimental order of the oxygen effects, CO > H_2CO > CO_2. However, the computed shifts of CO and CO_2, relative either to methane or to the isoelectronic hydrocarbons, are each roughly 100 ppm too large. The reasons for these large discrepancies are not clear, but for CO_2 may be associated with a tendency in this modified INDO framework for the calculation to give unrealistically small electron densities on carbon atoms to which oxygen atoms are attached, especially cases in which more than one oxygen atom is attached (see carboxylic acid results in Tables II and IV). For CO_2, the modified INDO calculation gives a carbon valence-shell density of 3.160; by comparison, CNDO/2 yields 3.463 and ab initio results yield 3.420.[15] For CO, the discrepancy between modified INDO and CNDO/2 is smaller, 3.831 vs. 3.959; the ab initio result is 3.804.[16]

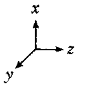
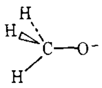
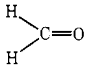
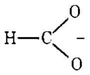
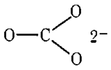
5. Ionic Species. For the anions represented in Table VI, it is seen that both the experimental and computed results show that for each case the carbon atom most closely associated with what is nominally the ionic center has a lower shielding than the corresponding carbon atom of the parent neutral. This is true in spite of the fact that the carbon atoms in question have higher computed electron densities in the anions than in the corresponding neutrals, except in the phenol/phenoxide case, where the computed electron densities are nearly the same.

The "ionization shifts" (difference between δ_C for the −1 anion and that of the parent neutral) are computed to be too large for all of the carbon atoms that are directly bonded to oxygen. This appears to be associated with the fact that the calculations are carried out on isolated species, and the effect of the excess electronic charge is accommodated by a relatively small structural entity. In experimental work the ions are part of a condensed phase and intermolecular interactions markedly influence the accommodation of the excess electrical charge. This point, which is explored further for the formate ion in a latter section of the paper, is likely to be the reason that the computed shift of $CH_3C{\equiv}O^+$, relative to $CH_3C{\equiv}CH$, is also considerably larger than the experimentally determined result.

The four computed carbon shifts of $C_6H_5O^-$ relative to either methane or phenol are in the experimentally correct order, except for a permutation of the results for the meta and para carbons. The computed oxygen effects ($C_6H_5O^-$ vs. $C_6H_5CH_3$) are all in the correct experimental order and of the correct sign.

6. Diagonal Tensor Elements. The entire discussion up to this point has centered upon the isotropic shift, which is equal to one-third of the trace of the chemical shift tensor and is the result obtained experimentally on liquid samples because of

Table VII. Shielding Tensor Elements of Selected C, H, and O Species Calculated by the Modified INDO Perturbation Method

	C, H, and O species[a]			Isoelectronic hydrocarbon[a,b]		
	σ_{xx} (σ_{pxx})	σ_{yy} (σ_{pyy})	σ_{zz} (σ_{pzz})	σ_{xx} (σ_{pxx})	σ_{yy} (σ_{pyy})	σ_{zz} (σ_{pzz})
	−44.0 (−105.3)	−44.0 (−105.3)	−9.8 (−62.6)	7.8 (−55.1)	7.8 (−55.1)	−6.4 (−60.0)
	−396.2 (−453.4)	3.1 (−66.0)	−174.3 (−215.5)	−251.9 (−313.4)	17.4 (−53.1)	−92.5 (−138.4)
$C\equiv O$	−437.6 (−503.9)	−437.6 (−503.9)	36.3 (0.0)	−130.0 (−200.1)	−130.0 (−200.0)	36.5 (0.0)
$O=C=O$	−338.3 (−406.4)	−338.3 (−406.4)	11.4 (0.0)	−209.8 (−282.7)	−209.8 (−282.7)	−110.1 (−133.1)
	−213.8 (−250.3)	−52.6 (−123.1)	−471.3 (−521.6)	−301.4[c] (−342.2)	15.7[c] (−56.3)	−386.2[c] (−437.8)
	−277.2 (−313.4)	−74.7 (−148.3)	−277.2 (−313.4)	−324.6 (−368.0)	26.4 (−47.8)	−324.6 (−368.0)

[a] Values in parentheses are the contributions of the paramagnetic terms to the corresponding total shielding tensor elements. [b] Taken from P. D. Ellis, Ph.D. dissertation, University of California, Davis, 1970, and ref 6, with one noted exception. [c] This work.

rapid tumbling. However, there are two recent experimental developments which have started to focus attention upon the individual elements of the shift tensor. These developments are: (1) the emergence of practical methods for making chemical shift anisotropy measurements, proton enhanced nuclear induction spectroscopy,[17] and (2) evidence that chemical shift anisotropy can provide a viable relaxation mechanism for ^{13}C experiments carried out at high fields.[18] Furthermore, in many respects, chemical shift anisotropies constitute a more critical test of a chemical shift theory than the isotropic shift. Individual elements of the shift tensor may vary considerably with a structural variation, while the isotropic shift could remain nearly constant because of compensating changes in different elements of the tensor.

Table VII collects the shielding tensor elements of selected species. For these species, the computed off-diagonal tensor elements are essentially zero, so the indicated axes can be considered the principal axes of the shielding tensors. It is interesting to compare the results in Table VII with previously reported results for the isoelectronic hydrocarbons.[6] One finds that the oxygen effect in CH_3O^- (relative to ethane) is largely associated with a lowering of σ_{xx} and σ_{yy}; σ_{zz} is changed only slightly. Upon viewing the separate diamagnetic and paramagnetic terms in the shielding (from eq 2 and 3, respectively), it is seen that the large decreases in σ_{xx} and σ_{yy} can be identified with large increases in paramagnetic circulations about the x and y axes upon substitution of $-O^-$ for $-CH_3$ on a methyl group. The small magnitude of σ_{zz} in both methoxide and ethane reflects the relatively high symmetry of the molecular electronic wave function about the z axis (C–C axis).

Comparing the formaldehyde results in Table VII with the earlier ethylene results, one finds that the main contributions to the oxygen effect on the shielding can be identified with σ_{xx} and σ_{zz}, both of which are substantially more negative in the formaldehyde case. Furthermore, these differences are almost entirely identifiable with the paramagnetic term. The order of the tensor elements, $\sigma_{yy} > \sigma_{zz} > \sigma_{xx}$, is the same for ethylene and formaldehyde.

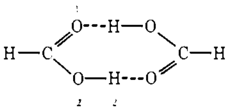
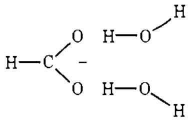
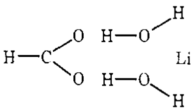
The results for carbon monoxide are interesting in relation to the corresponding acetylene values. Both σ_{xx} and σ_{yy} in CO are much more negative than the corresponding values in acetylene; σ_{zz} is almost identical for the two species. The large negative oxygen effect on σ_{xx} and σ_{yy} in this pair is identified with the paramagnetic contribution; the contribution of the paramagnetic term to σ_{zz} is identically zero in both species because of the perfect cylindrical symmetry in the molecular wave functions with respect to the z axis.

All three shielding tensor elements of CO_2 are substantially different than those in the isoelectronic hydrocarbon, allene. The σ_{xx} and σ_{yy} elements in CO_2 are nearly 120 ppm more negative in CO_2 than in allene, a difference identifiable almost completely with the paramagnetic term. By contrast, σ_{zz} is larger in CO_2 than in allene, reflecting the zero value in CO_2 resulting from the symmetry of the molecular electronic wave function.

There are large differences between σ_{xx} or σ_{zz} values for the formate ion and the corresponding results on the isoelectronic $(CH_3)_2{}^+CH$, and these differences are primarily identifiable with σ_p. The element σ_{yy} and its contribution from the paramagnetic term are algebraically the largest elements for both the formate and propyl ions. Ackerman, Tegenfeldt, and Waugh have measured the principal shift tensor elements in calcium formate.[19] The two crystallographically nonequivalent formate ions are both found to have shielding elements in the order $\sigma_{zz} < \sigma_{xx} < \sigma_{yy}$, where the orientation of the axes are approximately what is shown in Table VII. This is the same order as given for the computed results in Table VII. Although the computed shifts in the shielding tensor values (relative to the shielding of some standard) are substantially more negative than measured experimentally, especially for σ_{zz}, it should be recalled that the calculations were based upon an isolated, planar species. The experimental data, obtained on a crystalline sample, indicate that there is some distortion from planarity in the formate ions.[19]

The calculated shielding tensor of the carbonate ion bears some qualitative similarity to that of the previously computed results for the isoelectronic hydrocarbon, $(CH_3)_3C^+$. The isotropic shielding of $CO_3{}^{2-}$ is calculated to be slightly more negative than that of $(CH_3)_3C^+$; this difference results from less negative contributions of the paramagnetic term to σ_{xx} and σ_{zz}, compensated for by a substantially more negative contribution of the paramagnetic term to σ_{yy}. The contributions of the diamagnetic term to the tensor elements of $CO_3{}^{2-}$ are very similar to those of $(CH_3)_3C^+$ (or of $HCO_2{}^-$ and $(CH_3)_3CH^+$). It is gratifying to observe that, although the calculated results for carbonate are by no means quantitatively correct, the correct sign and general magnitude of the observed chemical shift anisotropy is obtained. Lauterbur has reported a study of calcite in which he observed that $\sigma_{yy} - \sigma_{xx}$ (or $\sigma_{yy} - \sigma_{zz}$) is 75 ppm, using the axis system shown in Table VII.[20]

Table VIII. Effects of Intermolecular Interactions on the Calculation of the Chemical Shifts of Formic Acid and Formate Ion[a]

	Geometry	$\Delta\delta_C$	ΔP	ΔP_π	ΔP_σ
	*b*	19.5	−18	−45	27
	*c*	−11.8	−50	−34	−16
	*c*	−19.2	−74	−53	−21

[a] $\Delta\delta_C$ and ΔP, ΔP_π, and ΔP_σ stand for the calculated chemical shift, electron density or π- or σ-orbital density of the carbon atom in the complexed species minus the corresponding quantity calculated for the uncomplexed species. [b] The geometry of the dimer employed is: $r_{H,C} = 1.08$; $r_{CO(1)} = 1.25$; $r_{CO(2)} = 1.36$; $r_{O(2)H} = 0.96$; $r_{H \cdots O} = 1.6$ Å; angles O(2)CO(1), H(1)CO(1), H(1)CO(2) are 120°; linear O· · ·H–O and linear H–C· · ·C–H. [c] The geometry of the complex has been reported previously: G. E. Maciel, J. W. McIver, Jr., N. S. Ostlund, and J. A. Pople, *J. Am. Chem. Soc.*, 92, 1 (1970).

7. Intermolecular Effects on ^{13}C Shifts. There has been a considerable amount of experimental evidence accumulated during the past dozen years on the influence of various intermolecular interactions on ^{13}C chemical shifts. In discussing some of the exaggerated oxygen effects of ionic species reported above, the probable importance of intermolecular interactions was pointed out. In this section, the results of modified INDO perturbation theory are used to explore the role of intermolecular interactions on the ^{13}C shifts of some model cases. While it would be unrealistic to base quantitative or detailed conclusions on the results, they should be useful for providing qualitative interpretative guidelines.

Table VIII summarizes results calculated for formic acid and the formate ion under conditions of modelled intermolecular interactions. The types of interactions that one hopes to model in these calculations are ion-dipole, dipole-dipole, ion-ion, and hydrogen bonding (partly overlapping with the other categories). The results in Table VIII show a substantial decrease in the shielding of a carboxyl carbon upon formation of the classic hydrogen-bonded dimer. This result is consistent with experimental data which imply that, among a variety of acetic acid solutions studied, the environments corresponding to the lowest carboxyl shieldings appeared to be those in which the dimer form of acetic acid predominates.[21]

The results on formate ion in Table VIII are also interesting. It is clear that inclusion of water in configurations for hydrogen bonding markedly improve the calculated chemical shift, relative to formic acid; i.e., the exaggerated "ionization shift" is reduced to a more reasonable magnitude. A further improvement is obtained by including some semblance of the presence of a counterion; Li$^+$ was used in the calculation for convenience. These results are consistent with earlier finite perturbation/INDO calculations on the spin-spin coupling between carbon and hydrogen in formate ion;[22] in those calculations it was found that the kinds of intermolecular interactions shown for the formate ion in Table VIII must be included in order to obtain sensible calculated coupling constants.

Table IX summarizes results on calculations of various exploratory dimer configurations of formaldehyde and water. The ^{13}C shifts of carbonyl groups are known to be sensitive to intermolecular effects, especially hydrogen bonding,[1] and these calculations were aimed at providing some theoretical guidelines for the interpretation of such shifts. The dimer configurations employed in the calculations summarized in Table IX are shown in Figure 1. Configuration I is simply the water-formaldehyde pair at infinite separation, for which the results of independent molecules are taken. Configurations II, III, IV, V, and VI are set up to represent reasonable structures for hydrogen bonding between a water proton and the carbonyl oxygen; some of them are analogous to configurations explored by Del Bene in ab initio calculations of energies.[23] Configurations VIII and IX are set up to model interactions between the carbonyl carbon and the oxygen atom of water. Configuration VII combines these two types of interactions. From previous INDO and CNDO work on hydrogen-bonded systems,[22] the O···H distance of a hydrogen bond was chosen to be 1.4 Å, a rather arbitrary and admittedly short value that appears to give results of reasonable magnitude in calculations at this level. It appears to be necessary to use unrealistically short O···H distances in CNDO and INDO calculations in order to capture the essence of the hydrogen bonding phenomenon. For the C···O interactions, distances ranging from 1.4 to 3.0 Å were explored.

Comparing the ^{13}C shifts calculated for the hydrogen-bonded complexes II–VI with that of independent formaldehyde (configuration I), it is seen that appreciable shifts of about 3–7 ppm to lower shielding are predicted for the hydrogen-bonded cases. This magnitude is consistent with shifts to lower shielding that have been observed for carbonyl compounds in

Table IX. Calculated Intermolecular Effects on Model $H_2O \cdots H_2CO$ Dimers[a, b]

	Formaldehyde									Water				
	Carbon				Oxygen			Hydrogen		Oxygen			Hydrogen	
Configuration	δ_C	P	P_π	P_σ	P	P_π	P_σ	P_1	P_2	P	P_π	P_σ	P_3	P_4
I	195.3	3.799	0.729	3.070	6.364	1.271	5.093	0.918	0.918	6.661	2.000	4.661	0.669	0.669
II	197.9	3.765	0.685	3.080	6.377	1.315	5.062	0.908	0.905	6.734	2.000	4.734	0.624	0.689
III	198.1	3.765	0.685	3.080	6.377	1.315	5.062	0.906	0.906	6.734	1.473	5.261	0.624	0.689
IV	199.0	3.765	0.682	3.083	6.371	1.318	5.053	0.898	0.904	6.749	2.000	4.749	0.624	0.687
V	199.7	3.765	0.679	3.086	6.373	1.272	5.101	0.898	0.898	6.762	2.000	4.762	0.619	0.684
VI	201.2	3.779	0.687	3.092	6.369	1.313	5.056	0.884	0.903	6.766	2.000	4.766	0.618	0.682
VII	176.1	3.717	0.666	3.051	6.455	1.372	5.083	0.931	0.931	6.658	2.000	4.658	0.637	0.671
VIIIa	250.1	3.740	0.716	3.024	6.480	1.320	5.160	0.862	0.862	6.600	1.983	4.617	0.728	0.728
b	212.8	3.791	0.719	3.072	6.428	1.287	5.141	0.887	0.887	6.652	1.993	4.659	0.677	0.677
c	201.4	3.796	0.715	3.081	6.400	1.286	5.114	0.902	0.902	6.673	1.998	4.675	0.664	0.664
d	196.6	3.796	0.719	3.077	6.380	1.281	5.099	0.912	0.912	6.673	2.000	4.673	0.664	0.664
IX	175.7	3.724	0.683	3.041	6.435	1.364	5.071	0.942	0.942	6.630	1.998	4.632	0.663	0.663

[a] Symbols defined in footnotes to Tables II and III. The π network is arbitrarily taken to be orthogonal to the plane containing the formaldehyde nuclei. [b] Geometries of the dimer configurations shown in Figure 1.

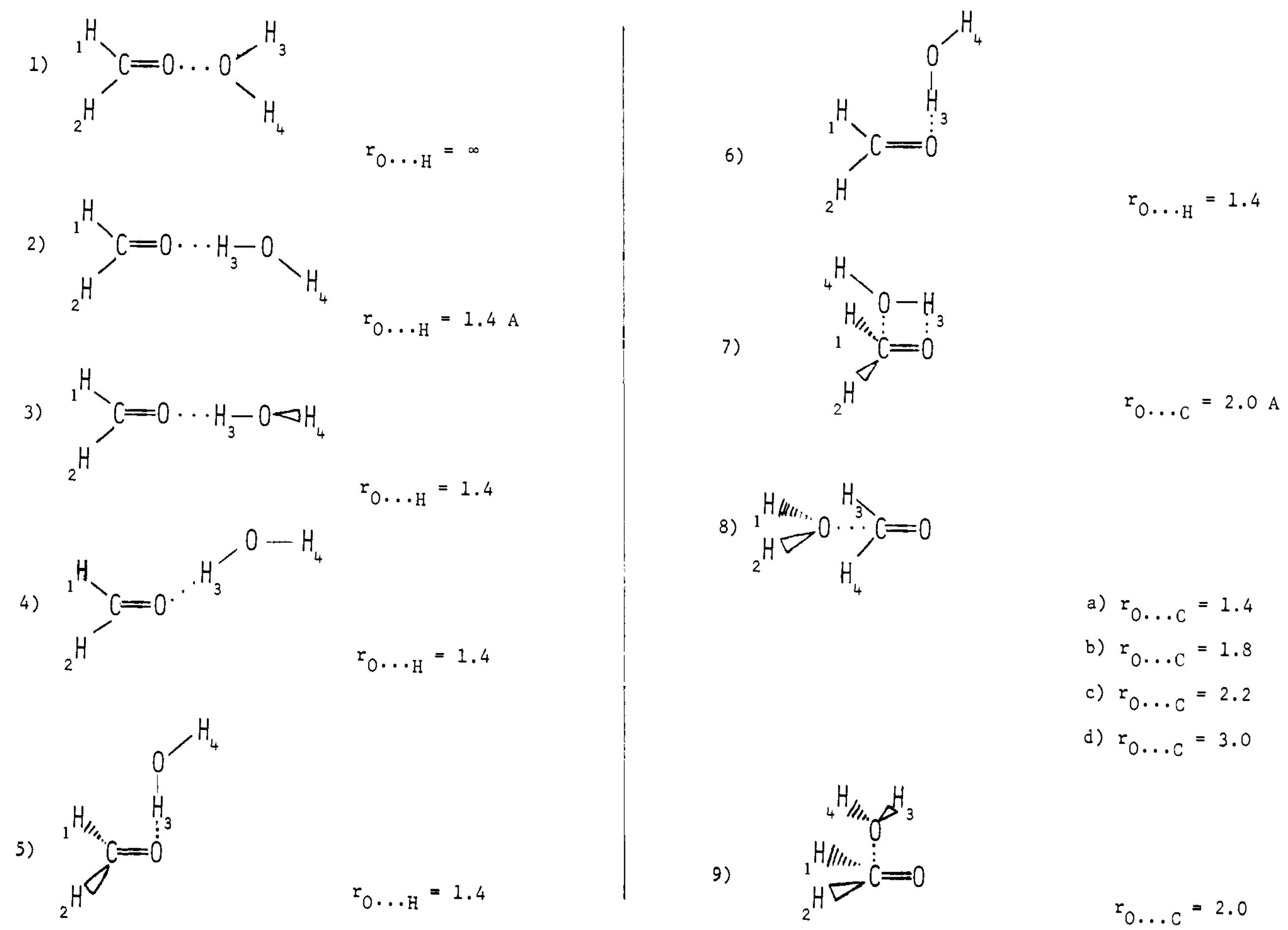
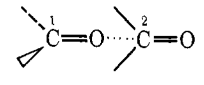


Figure 1. Geometries of formaldehyde-water dimer configurations employed in the calculations summarized in Table IX.

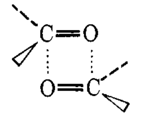
hydrogen-bonding media.[1] It is clear that interactions of the types represented by configurations VII and IX, both of which lead to large increases in shielding, are not consistent with experimental solvent effects in the direction of decreased shielding; however, transient interactions of this type may contribute to the shifts of carbonyl compounds in solvents containing basic functional groups. There is a rough, but not monotonic, trend of decreased shielding with decreased π-electron density of carbon in the hydrogen-bonded dimers, II–VI.

Somewhat surprisingly, the O···C interaction of the type represented by configurations VIIIa–d, in which the water and formaldehyde molecules are in perpendicular planes and with the C=O bond axis bisecting the H–O–H bond angle, also lead to decreases in ^{13}C shielding of the carbonyl carbon. It is interesting to note that inspection of the density matrix elements given in Table IX does not reveal any simple relationships between computed ^{13}C shifts and electron density elements for the closely related series, VIIIa–d. The results for configuration VIII imply that one must exercise caution in interpreting decreases in carbonyl shielding exclusively in terms of hydrogen bonding in media that contain basic as well as acidic centers, e.g., hydroxyl or carboxyl compounds. Interactions of this general O···C type, but between the oxygen atom of the carbonyl group of one molecule and the carbon atom of the carbonyl group of another molecule, might be suspected as being responsible for the fact that a lower shielding is observed for the carbonyl ^{13}C resonance of a pure carbonyl compound (e.g., acetone) than for a solution of the carbonyl compound dissolved in a hydrocarbon solvent (e.g., acetone in cyclohexane). Thus, interactions of the type X might be expected to show a decrease in shielding because of a O···C interaction (roughly type VIII) at the carbonyl carbon and also because of a ${}^{1}C{=}O\cdots{}^{\delta+}C{=}O^{\delta-}$ interaction (roughly type III, in which the positive side of the C=O dipole replaces a hydrogen-bonding hydrogen atom of water). However, a calculation on a formaldehyde dimer of type X (with $r_{C\cdots O} = 2.0$ Å) gave the results:



X

$\delta_{C(1)}$ 195.2 (essentially no change from isolated formaldehyde) and $\delta_{C(2)}$ 192.5 (a 2.5 ppm increase in shielding over that of isolated formaldehyde). Interestingly, a dimer of the type XI



XI

(with $r_{C\cdots O} = 2.0$ Å) gives a computed result of 203.1 ppm. A dimer of this type (with larger $r_{C\cdots O}$) has been shown by Del Bene's ab initio studies[24] to be energetically reasonably favorable; and transient interactions of this type may be at least partly responsible for the hydrocarbon dilution shifts of carbonyl carbons mentioned above.

Conclusions

By empirically choosing a set of atomic parameters for oxygen, the previously reported[6] SCF perturbation theory of ^{13}C chemical shifts at the (modified) INDO level has been extended from hydrocarbons to oxygen-containing compounds. The general structure trends of experimental ^{13}C shifts in alcohols, aldehydes, ketones, and carboxylic acids are reproduced satisfactorily by the theory, which tends to exaggerate the degree of electronic polarization generated by oxygen substitution into a hydrocarbon framework. The chemical shift anisotropies computed by the theory are in reasonable agreement with the sparse experimental data available.

The theory accounts satisfactorily for the experimentally demonstrated reduction of shielding of a carbonyl carbon due to hydrogen bonding to the carbonyl oxygen. Carbonyl–carbonyl interactions consistent with known dilution shifts can be rationalized by the calculations. The role of intermolecular interactions with the formate ion can be qualitatively accounted for in calculations in which these interactions are modelled.

Comparison of computed shifts and electron density elements reveals correlations only within a very narrow range of cases, e.g., within the set of four carbons of phenol or phenoxide.

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Conformational Analysis by Nuclear Magnetic Resonance. Nitrogen-15 and Carbon-13 Spectra of Lactams[1a]

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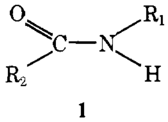
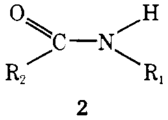
Abstract: The 5-, 6-, 7-, 8-, 9-, and 13-numbered lactams have been studied as simple models for the amide linkage. ^{15}N and ^{13}C spectra have been determined in various solvents and assignments made for the majority of the resonance lines. The ^{15}N and ^{13}C carbonyl chemical shifts show no apparent relationship to the amide ring size or to each other. The 9-membered lactam, azacyclononanone, exists as an equilibrium mixture of cis and trans conformers, the relative amounts of which depend on solvent and temperature. Carbon-13 NMR spectra of pure *trans*-azacyclononanone have been obtained from solutions of the solid at −45 °C in $CDCl_3$. At −35 °C two trans conformers are seen; at room temperature approximately equal quantities of the cis and trans isomers are present in ethanol, dimethyl sulfoxide, and tetrachloroethylene, whereas the cis conformer predominates in chloroform. Further increases in temperature cause rapid (on the NMR time scale) equilibrium between the two isomers such that a single averaged spectrum is seen at 120 °C. From the coalescence temperature of the carbonyl peaks the free energy of activation for the interconversion of *cis*- and *trans*-azacyclononanone is found to be 17 kcal/mol. This value is discussed in terms of the twofold periodic potential function for the distortion of amides from a coplanar conformation.

Lactams afford an excellent model system for a study of the amide group constrained in various conformations, such as might be found in cyclic peptides, large polypeptides, and proteins. We have made a systematic investigation of the ^{15}N and ^{13}C spectra of a series of closely related lactams to determine the relationship between ring size and conformations and the chemical shifts of ^{15}N and ^{13}C.

In open-chain N-monosubstituted amides, the trans conformation, **1**, is strongly preferred over the cis, **2**, as shown by dipole-moment measurements, as well as infrared, ultraviolet, and Raman spectroscopy.[2] Rotation about the C-N bond at room temperature is slow, the barrier to rotation being about 20 kcal mol^{-1} as determined by numerous NMR measurements[3] and, as first suggested by Pauling,[4] is ascribed to the partial double-bond character of the amide C-N bond.



1



2

In small-ring lactams, **3–6**, the amide group must, of necessity, adopt the cis conformation **2.** As the large rings approach the conformations of straight chain amides, they are, of course, found in the trans conformation **1.** The cross-over point, first detected by Huisgen[5] using infrared spectroscopy,