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Nuclear Spin–Spin Coupling via Nonbonded Interactions. 1. Conformational and Substituent Effects on Vicinal ^{13}C–^{1}H and ^{13}C–^{13}C Coupling Constants

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Abstract: Theoretical studies are presented for the conformational and substituent dependencies of vicinal ^{13}C-C-C-^{1}H and ^{13}C-C-C-^{13}C coupling constants. Calculated semiempirical INDO-FPT molecular orbital results are presented for the Fermi contact (FC) contributions in propane, butane, and a number of their derivatives. The calculated and observed decrease (increase) in the vicinal ^{13}C-H coupling constants due to electronegative (electropositive) substituents at the C2 carbon atom is rationalized in terms of the symmetry of the molecular orbitals entering the sum-over-states expression for the FC contributions. To investigate the importance of the large number of nonbonded interactions on the coupling constants, a modified INDO finite perturbation theory (FPT) procedure was adopted. Elements of the Fock matrices associated with orbitals centered on selected nonbonded pairs of atoms were set equal to zero in each SCF cycle, thereby eliminating these as coupling paths. On the basis of a large number of such calculations for propane and butane it is demonstrated that the nonbonded interactions are substantial for coupling to ^{13}C and can lead to important deviations from angular dependencies of the Karplus type.

The importance of nonbonded interactions in the transmission of the indirect coupling of the nuclear spins by the electrons has been recognized for some time. However, there have been few quantitative studies and recent work on coupling between nuclei other than protons has shown that the nonbonded interactions can be an exceedingly important factor for conformational and substituent dependencies. In this series of papers detailed theoretical and experimental results are presented to demonstrate the importance of the nonbonded interactions for vicinal ^{13}C-C-C-H and ^{13}C-C-C-^{13}C coupling constants.

The well-known theoretical study of the angular dependence of vicinal H-C1-C2-H coupling constants by Karplus[1] was based on a semiempirical valence-bond (VB) description of a six-electron fragment of the ethane molecule as depicted in Figure 1. The interactions (two-center exchange integrals) between nearest-neighbor atoms were the only ones included in the calculations; interactions between all other atoms such as the two hydrogen atoms, which are not bonded in the perfect pairing structure, were neglected. With these approximations the dependence of the vicinal H-H coupling constant $^{3}J_{HH'}(\phi)$ on the dihedral angle ϕ, measured about the C1-C2 bond, was shown[2] to be proportional to the exchange integral between the carbon hybrid orbitals (c_1 and c_2 in Figure 1) which are directed toward the coupled hydrogen atoms H_1 and H_2, respectively:[3]

$$^{3}J_{HH'}(\phi) = A\cos^2\phi + B\cos\phi + C \qquad (1)$$

For the case of vicinal H-H coupling, B in eq 1 is of opposite sign to A, and $C \ll A$. This gives the well-known angular dependence in which $^{3}J_{HH'}(180°) > {}^{3}J_{HH'}(0°)$, and $^{3}J_{HH'}(90°) \sim 0$. With a few exceptions, it has been assumed that vicinal coupling constants $^{3}J_{NN'}$ between nuclei other than hydrogen atoms in the N-X-Y-N′ moiety would also follow a dependence ("Karplus dependence") on the dihedral angle measured about the X-Y bond. Deviations from eq 1 become apparent in many cases in which one or both of the coupled protons are replaced by a first- or higher row element; these present many additional possibilities for bonding and substitution patterns. Contributions from terms other than the Fermi contact mechanism may also become important. In this series of papers it is clearly shown that substantial deviations from such angular dependencies occur because of the importance of nonbonded interactions,[4] which are not implicit in the form of eq 1, and which can become of greater magnitude than the bonded interactions, which led to the form of eq 1.

To determine the importance of the very large number of nonbonded electronic interactions for the ^{13}C-H and ^{13}C-^{13}C vicinal coupling constants, a modified INDO-FPT[5] molecular orbital procedure was adopted in this study.[6] Elements of the Fock matrices associated with orbitals centered on various nonbonded atom pairs were systematically set equal to zero in each SCF cycle, thereby preventing the transfer of unpaired spin density and, consequently, nuclear spin-spin coupling along that path. The results are found to be approximately additive for the systems of interest even though a very large number of coupling paths are involved.

Theoretical Section

Calculated coupling constant results presented in this series of papers were based on the finite perturbation theory (FPT) formulation[5] with the intermediate neglect of differential overlap (INDO) approximation of unrestricted self-consistent-field (SCF) molecular orbital (MO) theory.[6-10] In the

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Table I. Calculated INDO-FPT MO Results for Vicinal ^{13}C-H Coupling Constants in Propane, Dimethylpropanes, Difluoropropanes, and Propanoic Acid as a Function of the Dihedral Angle ϕ

dihedral angle ϕ	molecule, $^3J_{CH}(\phi)$, Hz propane	1,1-dimethylpropane	2,2-dimethylpropane	3,3-dimethylpropane	1,1-difluoropropane	2,2-difluoropropane	3,3-difluoropropane	1-propanoic acid
0	6.78	6.21	6.55	6.42	7.25	4.23	4.11	8.82
30	5.12	4.70	4.88	4.76	5.47	3.09	3.01	6.52
60	1.97	1.74	1.77	1.73	2.08	0.99	1.01	2.42
90	0.67	0.58	0.46	0.51	0.69	0.28	0.25	1.07
120	2.92	2.93	2.77	2.53	3.10	2.20	1.81	4.46
150	6.88	6.81	6.83	5.89	7.33	5.32	4.43	9.97
180	8.78	8.62	8.74	7.07	9.37	6.80	5.64	12.58
$\langle ^3J_{av} \rangle$[a]	4.24	4.03	4.09	3.51	4.51	2.93	2.55	5.81
$^3J_{exp}$	5.86[b]	c	4.65[d]	c	c	c	c	5.5 ± 0.2[e]

[a] $\langle ^3J_{av} \rangle = (1/3)[2(^3J_{CH}(60°)) + {}^3J_{CH}(180°)]$. [b] Wasylishen, R.; Schaefer, T. *Can. J. Chem.* **1974,** *52,* 3247. [c] Data not reported. [d] Karabatsos, G. J. *J. Am. Chem. Soc.* **1964,** *86,* 3574. [e] Karabatsos, G. J.; Graham, J. D.; Vane, F. M. *Ibid.* **1962,** *84,* 37.

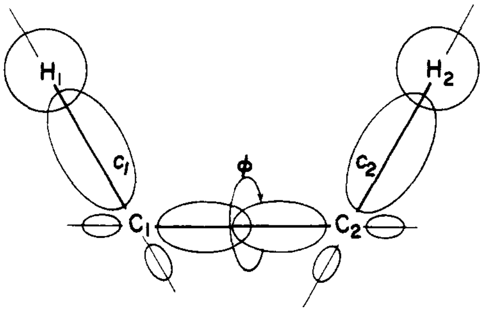


Figure 1. Schematic representation of a six-electron fragment of the ethane molecule; c_1 and c_2 denote the carbon hybrid orbitals directed toward the coupled hydrogen atoms H_1 and H_2. The dihedral angle ϕ is measured about the C_1-C_2 bond.

usual applications of this procedure,[5] the input data consists of the atomic numbers of the atoms and their molecular coordinates, and the calculated output includes MO eigenvalues, eigenvectors, and spin densities, in addition to the specified nuclear spin-spin coupling constants. On the basis of these data alone, it is exceedingly difficult to sort out the individual electronic factors which lead to the calculated coupling constant results. In previous studies we adopted an approximate procedure to estimate the importance of various coupling paths associated with the nonbonded interactions. This has been exceedingly useful for investigations of vicinal[11,12] and long-range H-H[13] and H-F[14] and vicinal ^{13}C-^{13}C coupling.[15]

In the INDO procedure[5] off-diagonal elements of the Fock matrices associated with both bonded and nonbonded atoms are of the form

$$F^{\alpha}_{\mu\nu} = (1/2)(\beta_A^0 + \beta_B^0)S_{\mu\nu} - P^{\alpha}_{\mu\nu}\gamma_{AB} \qquad (2)$$

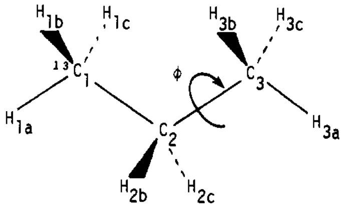
where $F^{\alpha}_{\mu\nu}$ is the off-diagonal element of the Fock matrix for electrons of α spin, β_A^0 and β_B^0 are empirical parameters for atoms A and B, $S_{\mu\nu}$ is the overlap integral between atomic orbitals μ and ν, $P^{\alpha}_{\mu\nu}$ is an element of the charge-density bond order matrix for electrons of α spin, and γ_{AB} is approximated as a Coulomb integral involving valence shell s-type orbitals for atoms A and B. A similar expression can be written for $F^{\beta}_{\mu\nu}$. In the previous qualitative discussions of coupling paths[11-15] it was found adequate simply to set the overlap integrals associated with particular sets of orbitals equal to zero. Partial justification for this simplified procedure was based on the small value of $P_{\mu\nu}$ associated with nonbonded atoms. However, it is now clear that this procedure is only qualitatively justified and contributions from the second term in eq 2 may be nonnegligible.[16] To clarify this and to sort out the small effects associated with ^{13}C-^{13}C and ^{13}C-H vicinal coupling constants, a modified procedure was adopted wherein the elements of the Fock matrices associated with the atoms of interest were set equal to zero in each SCF cycle, thereby preventing any "leakage" of spin density along the paths involving the atom pair. This revised procedure does not change the qualitative conclusions of the previous investigations.[11-15]

Molecular geometries were based on a standard geometrical model (SGM)[17] and all computations were performed on a Control Data Corp. CYBER 175 digital computer.

Results and Discussion

A. Vicinal ^{13}C-H Coupling Constants. 1. Conformational and Substituent Dependencies in Model Compounds. Because of the potential of experimental values of vicinal ^{13}C-H coupling constants $^3J_{CH}$ for conformational analyses, a fairly large experimental effort has been expended in establishing the dependence on dihedral angle and substituent effects.[18-26] A large number of calculated INDO-FPT results have been given by Wasylishen and Schaefer[27] for propane, substituted propanes, propenes, etc., and the results compared with the experimental data. Except for the propane values and the 180° value for 2,2-difluoropropane, their results are not duplicated in this study.

The calculated INDO-FPT results for the FC contributions to the vicinal $^3J(^{13}C1$-$H3)$ in propane (**1**), a number of disubstituted propanes, and 1-propanoic acid are entered in Table I at 30° intervals of the dihedral angle ϕ. The values for propane in Table I are no more than 0.03 Hz smaller in magnitude than the values given in ref 27, probably a result of our specification of the tetrahedral angles to eight significant figures rather than the SGM value of 109.47°.[17] The disubstituted compounds were used for the calculations to maintain a periodicity of 180° in the calculated results; in all cases the substituents replaced the *b* and *c* hydrogens in **1**. Results for single fluoro substituents at the 1a and 2b positions are given in ref 27.



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The propane $^3J_{CH}(\phi)$ values in Table I follow a dependence on dihedral angle of the form of eq 1:

$$^3J_{CH}(\phi) = 7.11 \cos^2 \phi - 1.00 \cos \phi + 0.67 \qquad (3)$$

Table II. Changes in the Magnitude of $^3J_{CH}$ Due to Inductive Substituents at the C2 Carbon Atom of a Propanic Fragment as Depicted in Figure 2

transition $i \to j$	sign of $c_{is}c_{ih}c_{js}c_{jh}$ [a]	sign of $^3J_{CH}(i \to j)$ [b]	change in $^3J_{CH}$ due to inductive substituent[c]
$4 \to 5$	+	−	> −
$3 \to 5$	−	+	> +
$4 \to 6$	−	+	...[d]
$2 \to 5$	+	−	> −
$3 \to 6$	+	−	> −
$4 \to 7$	+	−	> −
$1 \to 5$	−	+	...[d]
$2 \to 6$	−	+	...[d]
$3 \to 7$	−	+	> +
$4 \to 8$	−	+	...[d]
$1 \to 6$	+	−	< −
$2 \to 7$	+	−	> −
$3 \to 8$	+	−	> −
$1 \to 7$	−	+	...[d]
$2 \to 8$	−	+	...[d]
$1 \to 8$	+	−	< −

[a] The signs follow from eq 5 and 6 and Figure 2a. [b] Since the denominator in eq 6 is negative, the coupling contributions are of opposite sign to the product of the coefficients in the second column. [c] An electropositive substituent would have just the opposite effect. [d] Little or no change is expected for these excitations.

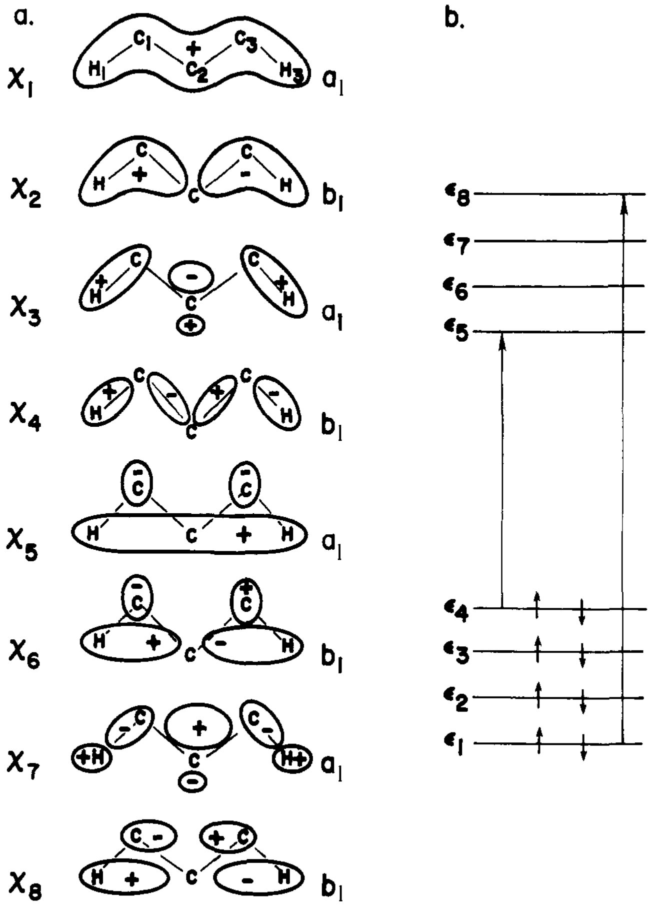


Figure 2. (a) Schematic representation of the nodal behavior and symmetry of the molecular orbitals in an eight-orbital fragment of the propane molecule. (b) A schematic representation of the occupied and unoccupied energy levels, ϵ_i, for the MOs depicted in (a).

Unfortunately, there are few experimental measurements of vicinal ^{13}C-H coupling constants which can be used to check the reliability of the computed conformational dependence as most of the experimental values in molecules of reasonably rigid structures have been obtained for cyclonucleosides[19,20] and carbohydrate derivatives.[18,24] Furthermore, a number of anomalies have been noted in the experimental results for dihedral angles near 180°.[24] Recently, using experimental results in model compounds having substituents at the C2 and C3 positions, an empirical equation for the angular dependence of $^3J_{CH}$ was proposed:[26]

$$^3J_{CH}(\phi) = 5.14 \cos^2(\phi - 5.3°) - 0.38 \cos(\phi - 5.3°) + 0.52 \quad (4)$$

where a phase shift of 5.3° was presumed to arise owing to the orientation of the C2 hydroxyl group relative to the C3-H3_a bond.[26,27]

Inspection of the data in Table I indicates that dimethyl substitution[28] at the C1 and C2 carbon atoms of **1** has very little effect on the calculated values of $^3J_{CH}(\phi)$. This is also the case for dimethyl substitution at the C3 carbon for dihedral angles less than 120°; $^3J_{CH}(180°)$ is 1.7 Hz less than the value for propane in Table I. This decrease has been ascribed to a γ-substituent effect[29] associated with the nonbonded interactions between hydrogens H1_b and H1_c and the hydrogens of the two C3 methyl groups.

The effects of difluoro substitution at each of the carbons C1-C3 on $^3J_{CH}(\phi)$ in Table I are substantial and reflect the importance of electron-withdrawing substituents. The vicinal ^{13}C-H coupling constants for 1,1-difluoropropane are more positive than the propane values over the whole range of dihedral angles, whereas difluoro substitution at C2 and C3 gives values which are uniformly smaller in magnitude. However, for angles greater than about 120° the $^3J_{CH}$ in 3,3-difluoropropane are somewhat smaller than the 2,2-difluoropropane values.

A rationalization of the decrease in the calculated and experimental[25] vicinal ^{13}C-H coupling constants on substitution at the C2 position of propane can be based on a qualitative MO description for an eight-orbital fragment of the propane molecule as depicted in Figure 2a, and a sum-over-states expression[30] for nuclear spin-spin coupling:

$$J_{CH} = (4h)^{-1}(16\pi\beta\hbar/3)^2\gamma_C\gamma_H\phi_{2s}^2(C)\phi_{1s}^2(H)\pi_{sh} \quad (5)$$

where π_{sh} is the mutual atom-atom polarizability associated with the 2s atomic orbital (s) on carbon and the 1s atomic orbital (h) on hydrogen:

$$\pi_{sh} = -4 \sum_{\substack{i,\text{occ} \\ j,\text{unocc}}} [\epsilon_j - \epsilon_i]^{-1} c_{is}c_{ih}c_{js}c_{jh} \quad (6)$$

The c's in eq 6 denote the coefficients of the 1s and 2s atomic orbitals in the occupied and unoccupied MOs with energies ϵ_i and ϵ_j, respectively. The symmetry arguments used here are completely analogous to those used to discuss the effects of substituents on geminal[31] and long-range[32,33] H-H coupling constants. The nodal behavior of the eight MOs and the corresponding symmetries appropriate to C_{2v} symmetry for the all-trans arrangement of the propanic fragment are depicted in Figure 2a. The ordering of the MO energies is shown in Figure 2b.

The signs of the products of the coefficients of the atomic orbitals in eq 6 are entered in the second column of Table II for each of the possible excitations from occupied to unoccupied MOs. The excitations specified in the first column are given in order of increasing energy. The signs of the contributions of each excitation to $^3J_{CH}$ (note that according to eq 5 and 6 these are opposite to the product signs) are given in the third column. Now consider the effect of the introduction of an electron-withdrawing substituent at the C2 carbon atom in Figure 2a; electron density will be removed from the bonding regions of the symmetric MO χ_1, and this will produce a de-

Table III. Calculated INDO-FPT MO Results for Vicinal ^{13}C-H Coupling Constants as a Function of Dihedral Angle on Excluding Selected Coupling Paths[f]

dihedral angle ϕ, deg	$^3J_{CH}$	$\Delta J_{CH}{}^a$	$\Delta J_{CH}{}^b$	$\Delta J_{CH}{}^c$	$\Delta J_{CH}{}^d$	$^3J_{CH}{}^e$
0	6.78	−0.90	−0.35	3.72	−0.52	4.10
30	5.12	−0.57	−0.31	2.85	−0.46	3.15
60	1.97	0.06	−0.19	1.09	−0.26	1.32
90	0.67	0.15	−0.18	0.06	0.05	0.64
120	2.92	−0.72	−0.37	0.68	0.44	2.06
150	6.88	−1.86	−0.56	2.16	0.72	4.43
180	8.78	−2.34	−0.62	2.91	0.77	5.58

[a] Elements of the Fock matrices associated with the valence atomic orbitals of the C1 and C3 carbon atoms were set equal to zero in this calculation. This is indicated by the notation $^*CH_3CH_2CH_3$. [b] $^*CH_3CH_2CH_3$. [c] $^*CH_3CH_2CH_3$. [d] $^*CH_3CH_2CH_3$. [e] *All* nonbonded interactions were set equal to zero in this calculation. [f] All values are in hertz.

crease in the carbon 2s and the hydrogen 1s atomic orbital coefficients c_{2s} and c_{1h}, respectively. Because of the orthonormality of the MOs, the 1s and 2s coefficients in the other symmetric MOs will be increased accordingly, but they will be unchanged in the antisymmetric MOs. In the last column of Table II are entered the changes in the magnitudes expected in $^3J_{CH}$ on substitution of an electron-withdrawing substituent at C2. Since the negative shifts strongly outweigh the positive shifts in the last column of Table II, the overall effect of electronegative substituents at C2 should lead to a decrease in the magnitudes of $^3J_{CH}$. Similarly, electropositive substituents at C2 are predicted to lead to increases in the values of $^3J_{CH}$. These conclusions are consistent with the available experimental results.[25] Unfortunately, symmetry arguments of this type become ambiguous for the cases of substituents at the C1 and C3 carbon atoms even though it is clear that electron polarization effects must be important in these cases as well.

In the last two rows of Table I are given the calculated values for the average ^{13}C-H coupling constants $\langle {}^3J_{av} \rangle$, based on the very simple assumption of the average of two gauche and one trans conformations. In nonrigid compounds such as these, where there are possibilities for interactions between methyl groups, it would be more appropriate to weight the values with the internal rotation barriers.[15] In the cases of propane and 2,2-dimethylpropane the calculated values are smaller than the observed ones. It has been noted previously[25] that the INDO-FPT method does not provide an adequate representation of the decrease in $\langle {}^3J_{av} \rangle$ for C2 methyl substitution. However, such a decrease is to be expected on the basis of the preceding arguments because a methyl group has a greater electronegativity than a hydrogen. The major inadequacy of the INDO-FPT method for these compounds may be due to an underestimation of $^3J_{CH}(180°)$ in the parent compound; if it is assumed that the 2-Hz values for $^3J_{CH}(60°)$ and $^3J_{CH}(300°)$ are reasonable, then a simple average of 5.8 Hz requires that $^3J_{CH}(180°)$ be about 13 Hz. This is more than 4 Hz greater than the value calculated for this angle. In contrast, the calculated value for propanoic acid in Table I is slightly larger than the observed one. The consistently larger values for the calculated values for propanoic acid are expected on the basis of the larger coefficients for the 2s atomic orbitals in a situation in which the C1 carbon is sp^2 hybridized. Comparisons of other calculated and experimental ^{13}C-H coupling constants will be given in subsequent papers in this series.

2. Effects of Nonbonded Interactions on $^3J_{CH}(\phi)$ in Propane. To investigate the importance of the many nonbonded interactions on vicinal ^{13}C-H coupling constants, a number of modified INDO-FPT calculations were performed for propane; elements of the Fock matrices between orbitals on nonbonded atoms were set equal to zero and the coupling constants were recalculated. These results are entered in Table III for 30° intervals of the dihedral angle. The values of $^3J_{CH}(\phi)$ for propane in Table I are entered in the second column. Columns 3-6 in Table III correspond to the *changes* $\Delta J^i{}_{CH}(\phi)$ in the calculated coupling constants:

$$\Delta J^i{}_{CH}(\phi) = {}^3J_{CH}(\phi) - {}^3J^i{}_{CH}(\phi) \tag{7}$$

where $^3J^i{}_{CH}(\phi)$ denotes the calculated value obtained on setting the interactions between the *i*th pair of atoms equal to zero. These differences reflect the contribution provided by coupling along path *i*. For example, the results $\Delta J^a{}_{CH}(\phi)$ in the third column of Table III were obtained from eq 7 on eliminating from the SCF calculations those elements of the Fock matrices associated with all of the valence atomic orbitals on the ^{13}C carbon C1 and all of the valence atomic orbitals of the C3 carbon atom of propane. The atoms involved in the path are set in boldface ($CH_3CH_2CH_3$). In this case the greatest change, $\Delta J^a{}_{CH}(180°) = -2.3$ Hz, occurs for the trans arrangement. In accord with our previous coupling-constant studies, the important nonbonded interaction in the trans arrangement is attributed to the importance of interactions of the "rear lobes" of the carbon hybrid orbitals such as would occur in localized MO descriptions.[15,30,34] For the path denoted *b* in Table III contributions associated with the valence atomic orbitals of C1 and the hydrogen atoms of C3 were set equal to zero ($CH_3CH_2CH_3$). These paths make relatively small contributions to $^3J_{CH}$, whereas for the path *c* interactions between the hydrogenic orbitals on C1 and the valence atomic orbitals of the C3 carbon atom make substantial positive contributions. For the case of path *d*, interactions between the hydrogens of C1 and the hydrogens of C3 were set equal to zero ($CH_3CH_2CH_3$), and it is noted that the $\Delta J^d{}_{CH}$ change sign as the C3 methyl group is rotated. In the last column of Table III are given the calculated values of the vicinal ^{13}C-H coupling constants $\Delta J^e{}_{CH}(\phi)$, which were obtained on setting all of the nonbonded interactions equal to zero in the same calculation, including several that were not considered separately. This is one reason for the lack of additivity of the nonbonded contributions. Nonadditivity of the calculated results is an important consideration as it indicates that this type of analysis may be interpreted at the qualitative level. Even though elements of the Fock matrices are not allowed to develop during the SCF calculation, interactions with many other atoms could still lead to coupling being transmitted by a particular atom. For example, in the calculations of $\Delta J^a{}_{CH}(\phi)$ in which matrix elements between valence-shell orbitals of C1 and C3 are zero, there are still paths in which these orbitals would be involved to varying degrees; the 1s atomic orbital of the coupled hydrogen H3$_a$ has large off-diagonal elements with the orbitals of C3, as do the latter with the orbitals of C2, and the orbitals of C2 with the orbitals of C1 (this is a "through-bond" coupling in the interpretation of ref 2).

Some of the other interesting features of the calculated results for nonbonded interactions of propane in Table III should be discussed; although contributions from a particular nonbonded path may be substantial, the various contributions cancel to a large extent in the final results. Perhaps the most surprising results in Table III are the large magnitudes asso-

Table IV. Calculated INDO-FPT MO Results for Vicinal ^{13}C-^{13}C Coupling Constants in Butane, Dimethylbutanes, Difluorobutanes, and Butanoic Acid as a Function of the Dihedral Angle ϕ

dihedral angle ϕ, deg	molecule, $^{3}J_{CC'}(\phi)$, Hz					
	butane[a]	1,1-dimethylbutane[b]	2,2-dimethylbutane[b]	1,1-difluorobutane[a]	2,2-difluorobutane[b]	butanoic acid[a]
0	5.79	1.42	5.57	2.30	4.20	1.76
30	3.96	3.43	3.74	1.96	2.73	2.27
60	1.97	0.37	1.77	0.88	1.34	1.24
90	0.56	0.47	0.45	0.55	0.28	0.71
120	1.45	1.45	1.24	1.63	0.84	2.14
150	3.34	3.25	2.86	3.61	2.09	4.65
180	4.27	4.11	3.44	4.59	2.69	5.87

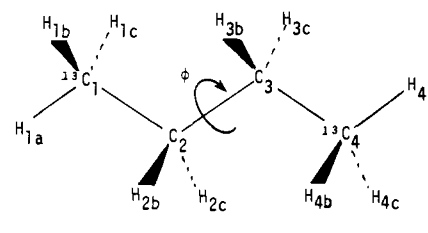
[a] Calculated values from ref 37. [b] 1,1- and 4,4-disubstituted compounds give identical results. [c] 2,2- and 3,3-disubstituted compounds give identical results.

ciated with path *c* ($CH_3CH_2CH_3$) corresponding to the nonbonded interactions between the orbitals of the C1 hydrogens and the valence atomic orbitals of C3. In another set of calculations it was shown that the hydrogen atoms of greatest importance for this nonbonded path are the proximate ones $H1_b$ and $H1_c$ in **1**. From the results in Table III it is reasonable to conclude that the nonbonded interactions are quite important for this type of coupling but that the interactions between orbitals on bonded atoms (C2 and C3 in **1**) dominate the conformational dependence of vicinal ^{13}C-H coupling and give an apparent dependence of the form of eq 1 and 3.

It is important to note that the procedure of setting selected *nonbonded* interactions equal to zero does not produce large changes in the electronic structure of the molecules and invalidate the coupling constant calculations. For example, in the case of propane the largest change in the total calculated INDO energies for the set of calculations *a*-*d* in Table III was an increase of 0.013 au for calculation *a*. In calculation *e*, which included *only* the interactions between bonded atoms, the total INDO energy was increased by 0.11 au.

B. Vicinal ^{13}C-^{13}C Coupling Constants. 1. Conformational and Substituent Dependencies in Model Compounds. Despite the usual necessity of using labeled compounds, a fairly large amount of data for vicinal ^{13}C-^{13}C coupling constants has been reported.[15,24,35-39] The role of conformation and substituents has been investigated experimentally in a series of carboxylic acids,[36] 1-butanols,[37] 2-butanols,[38] 1-substituted butanes, and C-11 substituted adamantanes.[15] Some unexpected results were found in these series of compounds, but it is now clear that these are due to the importance of previously unrecognized nonbonded interactions for vicinal ^{13}C-^{13}C coupling constants in the various series of molecules.

Calculated INDO-FPT results for vicinal ^{13}C-^{13}C coupling constants $^{3}J_{CC'}(\phi)$ in butane (**2**), butanoic acid, 1,1-dimethylbutane, and 2,2-dimethylbutane, and the various difluorobutanes are entered in Table IV for 30° intervals of the dihedral angle ϕ.[28] Because of the symmetry of the molecule, results for the 1,1-disubstituted and 2,2-disubstituted compounds are identical with those of the 4,4-disubstituted and 3,3-disubstituted compounds, respectively. Calculated results for butane and butanoic acid have been reported previously,[15,37] and it was noted that $^{3}J_{CC'}(0°) > {}^{3}J_{CC'}(180°)$ for butane and $^{3}J_{CC'}(0°) \ll {}^{3}J_{CC'}(180°)$ for butanoic acid. These findings are consistent with the experimental results in the series of 2-hydroxy-(1-hydroxy-[38]) butanes[37] and carboxylic acids,[36] respectively.



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The pattern of dimethyl substitution at the C2 carbon (or C3 carbon, by symmetry) is similar to that noted for $^{3}J_{CH}(\phi)$, i.e., a decrease of about 20% in $^{3}J_{CC'}(180°)$ but very little change for other dihedral angles. In contrast, for 1,1-dimethylbutane the values for 0 and 60° are substantially reduced below the butane values, whereas the calculated values for 30 and 90-180° are only slightly different. In the 0 and 60° orientations, pairs of hydrogen atoms are separated by only 0.735 Å in the SGM and the nonbonded interactions lead to substantial negative contributions to $^{3}J_{CC'}$. In fact, the smallest value for $^{3}J_{CC'}$ in 1,1-dimethylbutane occurs for $\phi = 60°$ in Table IV. Similar arguments must apply for the 1,1-difluorobutane as the calculated $^{3}J_{CC'}$ are greater than the butane values for dihedral angles greater than 90°, but they are smaller for dihedral angles smaller than 90° according to the calculated results in Table IV. For the 2,2-difluorobutane all of the calculated values are less than those for butane; this is expected on the basis of MO symmetry arguments completely analogous to those given for vicinal ^{13}C-H coupling in section A.1.

2. Effects of Nonbonded Interactions on $^{3}J_{CC'}(\phi)$ in Butane. The calculated INDO-FPT results for vicinal ^{13}C-^{13}C coupling constants in butane are given in Table V as a function of the dihedral angle ϕ. The second column is simply the unmodified results from Table IV. Columns 3-9 in Table V give the changes $\Delta J^{i}_{CC'}(\phi)$ in the calculated coupling constants:

$$\Delta J^{i}_{CC'}(\phi) = {}^{3}J_{CC'}(\phi) - {}^{3}J^{i}_{CC'}(\phi) \qquad (8)$$

where $^{3}J^{i}_{CC'}(\phi)$ denotes the calculated value obtained on setting the interactions between the *i*th pair of atoms equal to zero. These differences reflect the contribution provided by coupling along that particular path. For example, results $\Delta J^{a}_{CC'}$ in the third column of Table V were obtained from eq 8 and the value of $^{3}J^{a}_{CC'}$ obtained on eliminating all elements of the Fock matrices associated with the valence atomic orbitals on the C1 and C3 carbon atoms and the C2 and C4 carbon atoms. The results in Table V are more extensive than previous results for butane[15] and are presented in a format which emphasizes the importance of the various nonbonded interactions. In addition, it should be noted that there are some slight differences between the results in Table V and the results given in ref 15 as only the overlap terms in the Fock matrices were eliminated in the previous calculations.[15]

Results in columns 3-9 of Table V correspond to the elimination of the coupling paths between the following pairs of atoms (indicated by boldface letters in the formulas).

a. For $^{*}CH_3CH_2CH_2{}^{*}CH_3$ and $^{*}CH_3CH_2CH_2{}^{*}CH_3$, it was noted previously[15] that interactions between "rear lobes" of the carbon hybrid orbitals of C1-C3 and C2-C4 make substantial negative contributions in the trans arrangement of butane.

Table V. Calculated INDO-FPT MO Results for Vicinal $^{13}C-^{13}C$ Coupling Constants in Butane Excluding Selected Coupling Paths as a Function of the Dihedral Angle ϕ[h]

dihedral angle ϕ, deg	$^3J_{CC'}$	$\Delta J_{CC'}{}^a$	$\Delta J_{CC'}{}^b$	$\Delta J_{CC'}{}^c$	$\Delta J_{CC'}{}^d$	$\Delta J_{CC'}{}^e$	$\Delta J_{CC'}{}^f$	$\Delta J_{CC'}{}^g$
0	5.79	−1.53	−1.05	6.43	−4.35	−0.35	5.43	0.40
30	3.96	−1.04	−0.89	4.40	−3.22	−0.32	4.10	0.38
60	1.97	0.05	−0.51	1.72	−0.79	−0.19	1.77	0.28
90	0.56	0.17	−0.26	0.03	0.22	−0.01	0.23	−0.01
120	1.45	−0.55	−0.16	−0.18	0.28	0.34	0.54	−0.26
150	3.34	−1.44	−0.17	−0.13	0.15	0.62	1.72	−0.36
180	4.27	−1.79	−0.19	−0.10	0.10	0.70	2.34	−0.36

[a] All elements of the Fock matrices associated with the valence atomic orbitals connecting the C1 and C3 carbon atoms and connecting the C2 and C4 carbon atoms were set equal to zero in each SCF cycle ($*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$). [b] $*CH_3CH_2CH_2*CH_3$. [c] $*CH_3CH_2CH_2*CH_3$. [d] $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$. [e] $*CH_3CH_3CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$. [f] $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$. [g] $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$. [h] All values are in hertz.

b. For $*CH_3CH_2CH_2*CH_3$ it is not surprising that the elimination of the interactions between the valence atomic orbitals of the C1 and C4 carbon atoms is most important for the cis or 0° arrangement of butane.

c. For $*CH_3CH_2CH_2*CH_3$, in the cis arrangement of butane two of the methyl group hydrogens are separated by 1.84 Å in the SGM and lead to a substantial (6.4 Hz) positive contribution to the vicinal $^{13}C-^{13}C$ coupling constant. As the methyl groups are rotated away from one another contributions from this mechanism rapidly decrease and change sign for angles greater than 90°.

d. For $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$, the positive contributions from path *c* are substantially offset by the negative contributions provided by the orbitals of C1 and the 1s atomic orbitals of the hydrogens bonded to C4. These also decrease in magnitude and change sign as the methyl group is rotated away from the cis arrangement.

e. For $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$, contributions to the total coupling provided by these paths are relatively small, but the positive contributions associated with interactions of the hydrogen atoms on C2 and C3 will be shown to be an important factor for the γ-substituent effect on vicinal coupling constants, which will be discussed in the second paper in this series.[29]

f. For $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$, the complexity of the physical situation for vicinal $^{13}C-^{13}C$ coupling can be seen from the magnitude of the contributions associated with these coupling paths; they are comparable in magnitude to the total coupling constants given in the second column of Table V.

g. For $*CH_3CH_2CH_2*CH_3$ and $*CH_3CH_2CH_2*CH_3$, in contrast to the results for path *f*, interactions between these carbon and hydrogen orbitals make relatively small contributions to $^3J_{CC'}$, but change sign on rotation about the C2-C3 bond.

From the calculated nonbonded contributions to the vicinal $^{13}C-^{13}C$ coupling constants in butane in Table V it can be concluded that these dominate this type of coupling. As a consequence, it is not possible to obtain a satisfactory representation by the simple trigonometric relationship specified by eq 1. A most obvious reason for this is the importance of the nonbonded interactions near the cis arrangement. More generally, even in simple molecules there are an enormous number of possible nonbonded coupling paths, which can have substantial effects on vicinal and other types of coupling constants. In subsequent papers in this series the importance of the nonbonded interactions will be discussed in the context of some recent experimental data for vicinal $^{13}C-H$ and $^{13}C-^{13}C$ coupling constants.

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Nuclear Spin–Spin Coupling via Nonbonded Interactions. 2. γ-Substituent Effects for Vicinal Coupling Constants Involving ^{13}C

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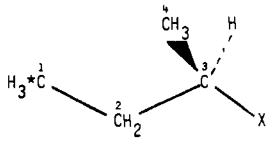
Abstract: The well-known γ effect on ^{13}C chemical shielding is shown to have a counterpart in vicinal coupling constants $^3J_{CX}$ involving a ^{13}C nuclear spin and a trans-oriented nuclear spin X. Experimental and theoretical results for vicinal $^{13}C1$–C2–C3–^1H and $^{13}C1$–C2–C3–^{13}C coupling constants in a number of C3-substituted aliphatic compounds in the trans arrangement and alicyclic compounds show a substantial decrease relative to the parent compound. By means of modified INDO–FPT molecular orbital procedures, which permit investigation of the importance of nonbonded interactions, it is shown that the γ-substituent effects arise in a complex way from the nonbonded interactions associated with groups bonded to the C3 or γ-carbon atom. A major factor is the *positive* contribution to $^3J_{CX}(180°)$ from the hydrogen atoms on the γ-carbon atom of the parent compound. Methyl groups on C3 make negative contributions; a major factor is the interaction between the hydrogen atoms of the C1 methyl and the hydrogen atoms of the methyl groups on the C3 carbon atom. It is further shown that other substituents also make *negative* contributions, and that hydrogen atoms on the γ substituents are not essential for the observation of a negative γ effect on vicinal coupling constants. The γ-substituent effects on vicinal ^{13}C–X coupling constants appear to be general phenomena of substantial magnitude; their recognition is important for conformational and other coupling-constant studies as they lead to results which appear to be anomalous.

Introduction

The γ effect on ^{13}C chemical shielding, which arises from gauche 1,4 carbon atoms,[3] has been used extensively in ^{13}C chemical shift assignments. The interpretation[3] in terms of a steric interaction model involving the hydrogens on the C1 and C4 carbon atoms in **1** has been questioned in some recent experimental[4] and theoretical studies.[5,6] In the present study experimental and theoretical results are used to demonstrate that substituents on the C3 or γ-carbon atom in **1** lead to a decrease in the magnitude of the vicinal coupling constants in the trans arrangement [$^3J_{CX}(180°)$] between the C1 and X nuclei. This appears to be a general result for vicinal coupling as well as shielding for cases in which hydrogens on the γ-carbon atom are replaced by other functional groups.[7,8]



1

By means of a modified molecular orbital procedure, described in the first paper in this series,[9] it is shown that the γ-substituent effect for vicinal coupling arises from the nonbonded interactions associated with the atoms on the γ-carbon atom; hydrogen atoms at the γ carbon make positive contributions to the vicinal ^{13}C–H coupling constants, whereas other substituents give negative contributions. There are also some indications of δ-methyl substituent effects on vicinal coupling constants, and these are of opposite sign to the γ-methyl effects, in complete analogy with the situation suggested for chemical shifts.[10]

Results and Discussion

1. γ-Methyl and Methylene Substituent Effects on Vicinal ^{13}C–^1H and ^{13}C–^{13}C Coupling Constants. Entered in Table I are the calculated INDO (intermediate neglect of differential overlap) finite perturbation theory[11] (FPT) molecular orbital (MO) results for for the Fermi contact (FC) contributions to vicinal ^{13}C–^1H and ^{13}C–^{13}C coupling constants (X = ^1H and $^{13}CH_3$ in Table I) for the trans (180°) arrangements of a number of aliphatic and alicyclic hydrocarbons. In all cases the standard geometrical model[12] (SGM) was used in the calculations. The similar patterns for vicinal ^{13}C–^{19}F coupling constants, which were noted in the preliminary results,[8] would be expected to follow throughout, but were not included in these more extensive tables. Experimental data from this study and available literature values are given in parentheses in Table I. In addition to the calculated results for propane and butane (**2**, X = H and $^{13}CH_3$, respectively), calculated results are given for molecules having one to four methyl groups in the C1, C2, and C3 positions (**3–16**) and for several cyclic molecules (**17–20**).

The calculated results for vicinal ^{13}C–H coupling in Table I clearly show that the effects of methyl substitution at the α (C1) and β carbon (C2) are small; the values for **3–6** differ from the propane coupling constant by less than 0.2 Hz. However, results discussed in part 1[9] suggest that there may be a decrease in $^3J_{CH}$ on C2 methyl substitution. It is interesting to note that successive methyl substitution at the γ- (C3) carbon atom (entries **7** and **8**, X = H) leads to a decrease in $^3J_{CH}$ of about 0.8 Hz per methyl group. In part 1[9] it was

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