On the Use of Geminal Coupling Constants of Methylene Protons Adjacent to Carbonyl Groups for Structural and Conformational Assignments

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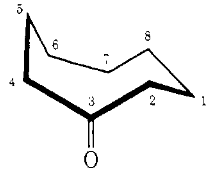
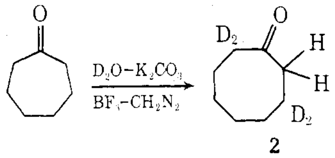
The analysis of the pmr spectrum of cyclooctanone-*2,2,7,7-d*$_4$ at −160° provides two values of geminal coupling constants: ^2J = −11.0 and −16.0 Hz. The least negative value is associated with the methylene protons on C(2) of the BC conformation (1) and demonstrates unambiguously that the prediction of the Barfield–Grant relationship is wrong in the vicinity of θ = 120° and, further, provides an order of magnitude for the positive contribution to ^2J from a carbonyl group predicted by molecular orbital calculations. The angular dependence of ^2J is discussed in light of these results.

In connection with another conformational study[1,2] we became interested in the precise relationship of the angular dependence of the geminal coupling constant characteristic of the methylene protons in the $-CH_2C(=O)-$ fragment. A brief review of the literature[3-10] has revealed that the graphical relationships obtained from semiempirical calculations[4,5] were generally valid but that uncertainties still persisted in the vicinity of θ = 120° [11] for which the two methods of calculations predict opposite effects—negative by the valence-bond approach[4] and positive by the molecular orbital approach.[5]

It appears that experimental verification of theory has been hampered by the fact that relatively few compounds of known rigid conformation have the particular geometry of interest. This situation led us to investigate cyclooctanone, whose stable conformation is known to be a boat-chair (BC, 1)[12] for which molecular models suggest pertinent geometrical dispositions between the carbonyl group and the adjacent methylene groups at positions 2 and 4.



1



2

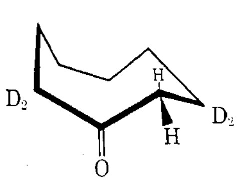
Consequently the partially deuterated cyclooctanone-*2,2,7,7-d*$_4$ (2), having a simplified ^1H NMR spectrum, was prepared from cycloheptanone as shown above through α-deuteration followed by ring expansion with diazomethane.[13]

Results and Discussion

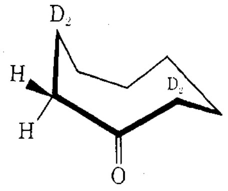
The 100-MHz deuterium-decoupled ^1H NMR spectrum of 2 at 25° shows a singlet at δ 2.36 (α-CH_2), a band centered at δ 1.9 (2 H), and a broad band centered at δ 1.5 (6 H). Figure 1 illustrates the spectral changes occurring as the temperature is lowered. At −135°, the AB quartet ($\Delta\nu \approx$ 48 Hz and $^2J \approx -14$ Hz) observed at low field is easily recognized as arising from the α-CH_2 protons; the apparent asymmetric intensities observed are caused partly by greater exchange broadening of the downfield doublet and partly by the superposition of the upfield doublet on a very broad band arising from a change in the signal originally at δ 1.9. The left half of the quartet is seen to broaden significantly at −145°, whereas the lines of the right half remain much narrower. Eventually at −160°, two AB are easily recognized as characteristic of the α-CH_2 protons of 2 (the line diagrams under the spectrum identify each quartet). Overlapping with the broad signal again accounts for the observed departure from symmetric intensities.

The spectral lines of the AB patterns are naturally broad at this low temperature[14] but it is nevertheless possible to determine precise values for the ^1H NMR parameters. Analysis provides $\Delta\nu$ = 73.0 ± 0.5 Hz and ^2J = −11.0 ± 0.3 Hz for one quartet and $\Delta\nu$ = 29.5 ± 0.5 Hz and ^2J = −16.0 ± 0.2 Hz for the other quartet.

The spectral changes observed are characteristic of the slowing down of both pseudo-rotation ($\Delta G^\ddagger$ = 6.3 kcal/mol) and ring inversion ($\Delta G^\ddagger$ = 7.5 kcal/mol) for cyclooctanone[12] such that at −160° the spectrum contains signals characteristic of the two different methylene groups in the two possible diastereomeric BC forms of **2**, namely **2a** and **2b**. Consequently each of the two ^2J values measured must be assigned to one of these diastereomers [*i.e.*, to the methylene protons on either C(2) or C(4) of the BC conformation].

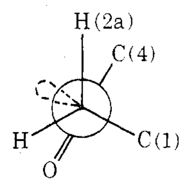


2a

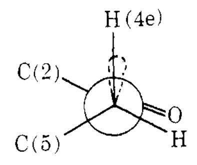


2b

Molecular models reveal that the relationships between the α-CH_2 protons and the carbonyl group in **2a** and **2b** are as shown by structures **3a** and **3b**, respectively. The first one represents the projection about the C(2)–C(3) bond of BC and shows that the π-orbital lobe and methylene protons are essentially staggered; thus the expected ^2J value is equal to that predicted for a dihedral angle (θ) near 120°. On the other hand, **3b** illustrates the projection about the C(4)–C(3) bond and shows that the π-orbital lobe and H(4e) are essentially eclipsed; the expected ^2J value is then predicted for θ near 0°.[4] It is therefore clear[3-10] that the



3a



3b

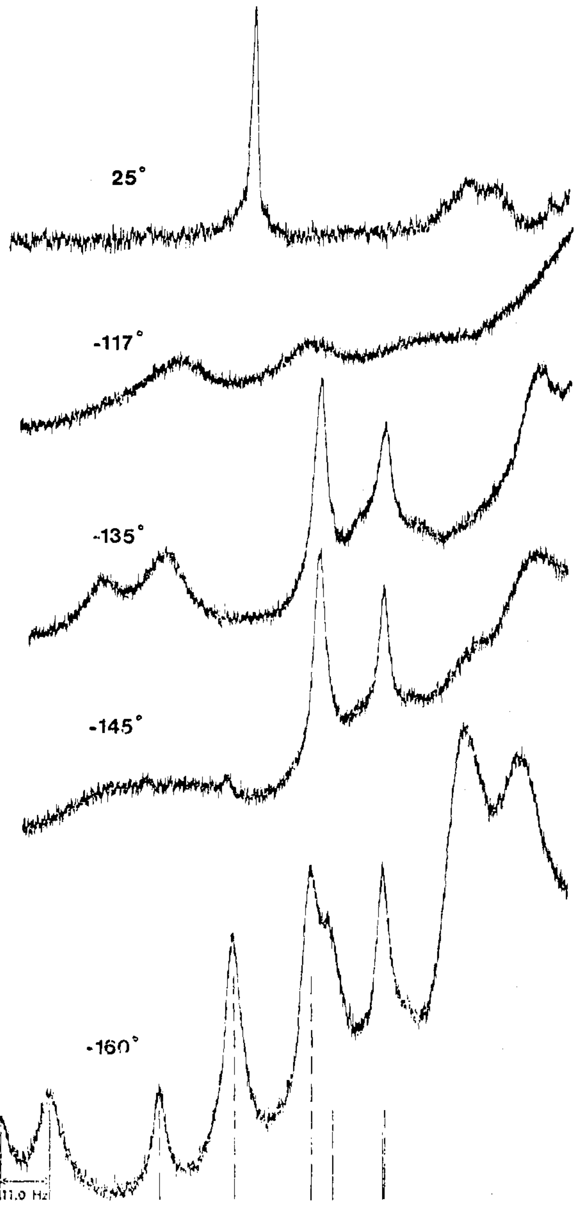


Figure 1. The 100-MHz deuterium-decoupled ^1H NMR spectrum of the two lower field signals of 2 at 25° and the spectral change observed at lower temperatures.

less negative coupling constant (−11.0 Hz) must be associated with the C(2) methylene protons while the more negative coupling (−16.0 Hz) must be associated with the C(4) protons.

There exists ample evidence[6,7] illustrating that ^2J is also dependent on the magnitude of the C-CH_2-C angle. Accordingly it must be noted that this angle is undoubtedly larger in cyclooctanone than in either methane or cyclohexane. Estimates of 115–117° are realistic[15] and consequently the reference value to which contributions (ΔJ) from the π-bond orientation are to be referred should be more negative than −12.4 (methane) or −13.0 Hz (cyclohexane).[3,4] The value of −14.3 Hz determined for cyclooctane-d_{14}[16] is probably the most appropriate reference on which a semiquantitative rationalization of our results can be based. Consequently the empirical value of $\Delta J = -1.7$ Hz for the protons on C(4) shows excellent agreement with an estimate for $\theta \simeq 0°$ predicted theoretically from the Barfield–Grant relationship.[4] On the other hand, the value of $\Delta J = +3.3$ Hz for the protons on C(2) definitely contradicts the prediction for $\theta \simeq 120°$. This positive contribution to ^2J, in fact, agrees with the qualitative prediction of the molecular orbital theory[5] and essentially fixes the order of magnitude for such a positive contribution by a carbonyl group.

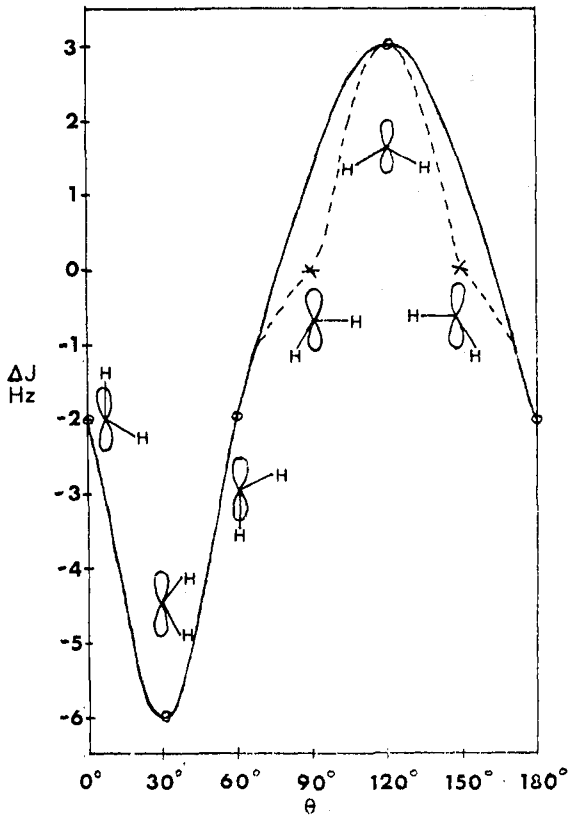


Figure 2. Graphical representation of the effect of the dihedral angle (θ) between a methylene group and the π lobes of an adjacent carbonyl group on ^2J. The small drawings illustrate the projection of the methylene protons on the π bond for several values of θ.

Because of the uncertainty in depicting the absolute disposition of the carbonyl group in 1 from molecular models, the above ΔJ values must not be interpreted in the most quantitative sense. The important significance is that, in the range of 0 to 180° for θ, $\Delta J \cong -2$ Hz is a good estimate of the carbonyl contribution for θ in the vicinity of 0, 60, and 180°, while $\Delta J \cong +3$ Hz is a good estimate of the carbonyl contribution for θ in the vicinity of 120°.

Molecular orbital calculations[5] have shown that the negative contribution ($\theta = 0$ to $\sim 90°$) is caused by hyperconjugative electron withdrawal from the antisymmetric orbitals of the CH_2 group, whereas the positive contribution ($\theta \sim 90$ to $\sim 150°$) is caused by electron withdrawal from the symmetric orbitals. The theory also predicts that both effects should be essentially null at 90°.

Although the absolute values of ΔJ for $\theta = 30$ and 90° are not known with great precision, the value of −6 Hz has been proposed as an estimate for $\theta = 30°$ from a consideration of experimental data.[4,6,7] Experimental evaluation of ΔJ near 90° has involved the analysis of cyclohexanone derivatives for which $\theta \approx 86°$ [7] and it has been found that ΔJ is indeed close to zero.

The ambiguity in the vicinity of 120° having been removed convincingly by our results, it is therefore tempting to draw a curve as in Figure 2 to illustrate graphically the angular dependence of ΔJ with θ. Two possibilities are shown near 90° (solid and dotted lines) and it is difficult to choose between them at the present. It is, however, reassuring that the difference between both lines is within 1 Hz. Since experience[6,7] has shown that such a curve should in practice be visualized as a narrow band to reflect uncertainties arising from factors not related to the presence of the carbonyl group, the difference between the two lines is not very significant for practical applications. On the other hand, analytical expressions describing the precise behavior are dependent on the ΔJ value at 90° and it appears desirable to wait for more experimental results before attempting to evaluate empirically the constants involved in such expressions.[4,10b]

Accordingly, the relationship shown in Figure 2 illustrates clearly that many structural alternatives involving a carbonyl group can be identified confidently in a practical way and the great insight into the local environment of the carbonyl group of the BC conformation of cyclooctanone provided by the ^2J values of 2 further stresses the power of geminal couplings as a sensitive probe for specific conformational relationships.

Experimental Section

The VPC analyses and separation were carried out on a Varian Aerograph A90-P3 instrument using helium as carrier gas.

The ^{1}H NMR spectra were obtained at 100 MHz on a 5% solution of cyclooctanone-*2,2,7,7-d_4* (2) in chlorodifluoromethane containing a small quantity of Me_4Si in a tube which had been degassed and sealed. The instrumental details and procedures are as described earlier[17] with the exception that temperatures are reported to ±1° since greater precision was not necessary in this work.

Preparation of Cyclooctanone-*2,2,7,7-d_4* (2). Cycloheptanone (1.5 g), 60 ml of D_2O, and 6.0 g of K_2CO_3 were refluxed for 5 hr. After cooling, the ketone was extracted with ether. The ether solution was then dried with $MgSO_4$ and its volume was adjusted to 30 ml.

Freshly distilled boron trifluoride etherate (1 ml) was added to the solution followed by portions of a diazomethane solution in ether[13] while stirring adequately. Aliquots of the reaction mixture were taken periodically and analyzed by VPC using a Carbowax 20M column at 175° in order to monitor the extent of ring expansion. The reaction was stopped when the chromatogram suggested that about 60% of the mixture was cyclooctanone. Water (20 ml) was added and the ether layer was then separated and washed with a saturated solution of $NaHCO_3$ and with water and then dried over $MgSO_4$. The solution was concentrated and the cyclooctanone present was isolated by preparative VPC using a UC-W-98 column (15 ft × 0.375 in., 165°).

Reinjection of the isolated product on a Carbowax column showed it to be free of other ketones and to have the same retention time as an authentic commercial (Aldrich) sample of cyclooctanone. The ^{1}H NMR spectrum (Figure 1) shows that the isotopic purity of the cyclooctanone-*2,2,7,7-d_4* (2) thus prepared is sufficient for the planned study.

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Registry No.—2, 53927-13-2; cycloheptanone, 502-42-1.

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Formation and Interconversion of Allene Dimers via Bisallyl Diradicals. Possibilities on and Documentation of the Supergraph

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A coding system is developed to handle interconversions among 1,2-dimethylenecyclobutanes (D) and associated planar (P) and orthogonal (O) bisallyl diradicals. In the most general case, a graph of 320 edges links the 64 D's, 32 P's, and 32 O's. Compact labels for the species and algorithms for interconversion steps DO, OP, etc., have been devised. Relationships among those D's, P's, and O's which formally originate in the allene KHC=C=CHK are summarized in several graphs.

Graph theory or systems analysis[1] has recently been applied to isomerizations. That is, given species ML_n, e.g., a trigonal bipyramid or octahedral complex, one can describe all of the permutational isomers and their isomerization paths either by a graph or in a topological representation.[2] For example, the graph of the 1,2 rearrangements of the carbocation $R_1R_2R_3C{-}CR_4R_5^+$ involves 30 distinct interconversions (edges) among the 20 isomers (points).[2a] Here we wish to focus on an example of complex genealogy in allene dimer chemistry in which three different structural types, each with its set of permutational isomers, are variously connected by bond-making, bond-breaking, and conformational interconversions. A graph derived for this system may be regarded as a projection of the energy hypersurface on which these species lie, through which reactant coordinates pass, and with which mechanisms must be consistent. The important feature that deserves emphasis is that the present approach can be generalized to even more complex systems in which groups of species of different symmetries are interconvertible.

A common entry into the 1,2-dimethylenecyclobutanes is via allene dimerization.[3]