agreement with the strength of the donor–acceptor interaction indicated by the frontier orbitals.

The second example concerns energetically low-lying structures of $C_6H_6^{2+}$ as reported in a theoretical investigation by Lammertsma and Schleyer.[9] The number of possible isomers is very high, and a qualitative model to predict stable structures will aid the search. As noted before, analogy to neutral isomers is no help. Thirteen structures are reported, and three (A, B, C) were found to be candidates for the global minimum.

Again, this could have been predicted on the basis of our model. In our study we found the strongest bonding between CH_2^{2+} as acceptor and CH_2 ($^1A_1$) as donor. All three low-lying $C_6H_6^{2+}$ isomers A, B, and C correspond formally to donor–acceptor complexes between CR_2^{2+} and singlet carbenes. In case of A, planarity is found due to stronger π-conjugation relative to hyperconjugation.[42]

One referee argued that, based on our model, more stable structures should be expected with CR^{2+} as donor rather than CR_2^{2+}. In fact, one of the 13 isomers for $C_6H_6^{2+}$ reported in ref 9 represents a donor–acceptor complex between CH^{2+} and C_5H_5, but it is much higher in energy compared to A, B, or C. This can be explained by the very unfavorable overlap between donor and acceptor unit in this structure which forms a pyramidal geometry with an apical CH^{2+} acceptor and basal C_5H_5 donor.[9]

It seems that no suitable donor unit for C_5H_5 can be formed which can interact in a favorable way with CH^{2+}. In this context it is interesting to learn that in the meantime the same 13 structures have been calculated for the triply charged $C_6H_6^{3+}$ isomers.[45] Again, structures A, B, and C were found as energetically lowest lying species, but the stability differences were found to be larger at the same level of theory.[45] It seems that the differences in donor–acceptor interaction become more pronounced in higher charged species.

Our analysis of donor–acceptor interaction does not cover all kinds of possible orbital interaction. For example, stable structures may arise from donor–acceptor interaction involving π-donors. Hexacoordinated pyramidal carbodications, a well-known class of cations which is even stable in solution,[2,11] can be explained by the interaction between an apical RC^{2+} acceptor and a basal π-donor. Thus, the model of donor–acceptor interaction may still be extended.[46]

It is more the rule than the exception that the structure of a doubly charged species is substantially different compared to the respective neutral molecule. The simple model presented here is of great value for predicting structures of stable dications.

(42) For a discussion and further examples of planar, substituted ethylene dications see ref 35.

(43) This is a qualitative approach to demonstrate the basic principle. A more detailed account of frontier orbital interaction has to consider orbital coefficients. For example, the different reaction energies when CO donates electronic charge via oxygen or carbon may be explained by the larger coefficient at carbon for the lone-pair HOMO. For further discussion of frontier orbital interaction, see ref 21.

(44) The total energy of CF_2^{2+} at MP3/6-31G*//6-31G* is –235.9412 hartrees. The geometry was taken from the following: Koch, W.; Frenking, G. *Chem. Phys. Lett.* **1985**, *114*, 178.

(45) Koch, W.; Schwarz, H. *Chem. Phys. Lett.* **1985**, *113*, 145. A different analysis has been given by the following: Jemmis, E. D.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1982**, *104*, 4781.

(46) A different analysis has been given by the following: Jemmis, E. D.; Schleyer, P.v.R. *J. Am. Chem. Soc.* **1982**, *104*, 4781.

Barriers to Rotation Adjacent to Double Bonds. 2. *n*-Propyl vs. Isopropyl Groups

Kenneth B. Wiberg

Contribution from the Department of Chemistry, Yale University, New Haven, Connecticut 06511. Received March 28, 1986

Abstract: The barriers to rotation about the C–C bonds adjacent to the carbonyl groups of isobutyraldehyde, methyl isopropyl ketone, and isobutyric acid were calculated. The 3-21G basis set was used for the geometry optimizations, and the 6-31G* basis set was used to obtain the energies. The differences in energy between R = *n*-propyl and isopropyl also were calculated and reproduced the observed energy differences. Whereas the more branched isomer had a significantly lower energy for the aldehydes and acids, the difference in energy was very small with the ketones. The components of the barrier are discussed. The traditional decomposition into 1-, 2-, and 3-fold terms does not provide a useful representation of the interactions which are involved. Besides the 3-fold barrier observed with compounds having R = CH_3, the major contributions to the barrier arise from the stabilizing interaction between an alkyl group and the carbonyl ($\sim$1 kcal/mol) and from the repulsive interaction between one of the methyls of the isopropyl group and the other substituent at the carbonyl. A hydroxy group (i.e., in a carboxylic acid) leads to a significantly smaller steric interaction than found with a methyl group (i.e., in a methyl alkyl ketone).

The conformations of ketones have been of considerable interest in connection with studies of stereoselection in addition to the carbonyl group. Models for the addition have been developed by Cram,[1] Cornforth,[2] Karabatsos,[3] Felkin,[4] and others.[5] Theoretical studies of the activated complexes for addition to carbonyl groups by Ruch and Ugi,[6] Salem,[7] and especially Anh and Eisenstein[8]

(1) Cram, D. J.; Abd Elhafex, F. A. *J. Am. Chem. Soc.* **1952**, *74*, 5828.
(2) Cornforth, J. W.; Cornforth, R. H.; Mathew, K. K. *J. Chem. Soc.* **1959**, 112.

(3) Karabatsos, G. J. *J. Am. Chem. Soc.* **1967**, *89*, 1367.
(4) Cherest, M.; Felkin, H.; Prudent, N. *Tetrahedron Lett.* **1968**, 2201. Cherest, M.; Felkin, H. *Ibid.* **1968**, 2205.
(5) For a summary of previous studies, see: Wipke, W. T.; Gund, P. *J. Am. Chem. Soc.* **1976**, *98*, 8107.
(6) Ruch, E.; Ugi, I. *Top Stereochem.* **1969**, *4*, 99.

Table I. Rotational Barrier and Structure for Acetic Acid

a. Energies[a]

conformer	3-21G/3-21G		6-31G*/3-21G		6-31G*/6-31G*		obsd
	E	ΔE	E	ΔE	E	ΔE	
eclipsed	−226.534 24	0.00	−227.808 58	0.00	−227.810 65	0.00	0.00
staggered	−226.532 92	0.82	−227.808 00	0.36	−227.809 69	0.60	0.48

b. Structure[b]

| unit	eclipsed			staggered	
	3-21G	6-31G*	obsd	3-21G	6-31G*
r(C—C)	1.498	1.502	1.517 ± 0.015	1.502	1.505
r(C=O)	1.202	1.187	1.212 ± 0.009	1.203	1.188
r(C—O)	1.360	1.332	1.361 ± 0.009	1.358	1.330
r(O—H)	0.969	0.952		0.969	0.953
r(CH)[a]	1.078	1.079	1.100 ± 0.030	1.076	1.080
r(CH)	1.083	1.084		1.083	1.083
C—C=O	127.44	125.81	126.6 ± 1.8	126.56	124.68
O—C=O	122.09	122.36	123.0 ± 1.8	122.00	122.38
C—C—O	110.47	111.82	110.6 ± 0.2	111.44	112.93
C—C—H[c]	109.66	109.58		110.43	111.88
C—C—H	109.37	109.64		109.20	108.68
C—O—H	111.79	108.10		111.72	108.02
H—C—H	107.73	107.68		107.62	107.67

[a] Energies are given in hartrees (1 hartree = 627.5 kcal/mol) and energy differences are given in kcal/mol. [b] Bond lengths are given in Å and angles are given in deg. [c] Unique hydrogen.

have contributed to an understanding of the problem. The direction of addition to the carbonyl group has been examined via X-ray crystallographic studies,[9] by theoretical calculations,[9,10] and by experimental studies using specially designed substrates,[11] and an angle of attack of ∼110° appears to be well established. Despite these studies, there are aspects of these reactions which are not fully understood.

Two of the important factors that must be considered are the ground-state conformations and the barrier to rotation about the C—C bond adjacent to the carbonyl. Although it is well established that *n*-alkyl groups perfer to eclipse the carbonyl,[12] the conformations and barriers to rotation for α-branched alkyl groups remain in question.[13] The ground-state barrier is, of course, not the only important factor in determining the direction of addition to a carbonyl group, but it will be difficult to achieve an understanding of the factors that control the barrier in the activated complexes for reaction without first determining the nature of the ground-state interactions. In view of the importance of stereoselective additions to carbonyl in designing synthetic strategies, a detailed study of the barriers to rotation would appear to be of considerable value.

We also have been interested in this problem for a different reason. Steric effects are frequently observed in the conversion of a trigonal carbon to tetrahedral because the decrease in bond angles at the carbon in question will bring the substituent groups closer together and will amplify steric repulsion. We have used the reverse reaction (i.e., tetrahedral to trigonal), as found in the hydrolysis of acetals,[14] ketals,[15] and ortho esters,[16] as a tool in obtaining quantitative information on steric effects.

(7) Salem, L. *J. Am. Chem. Soc.* **1973**, *99*, 94.

(8) Anh, N. T.; Eisenstein, O. *Tetrahedron Lett.* **1976**, 155. At the time this important study was carried out, it was not practical to carry out geometry optimization or to use a basis set larger than STO-3G. Therefore, there are some aspects of this study which deserve reinvestigation.

(9) Burgi, H. B.; Dunitz, J. D.; Lehn, J. M.; Wipff, G. *Tetrahedron* **1974**, *30*, 1563.

(10) Eisenstein, O.; Schlegel, H. B.; Kayser, M. M. *J. Org. Chem.* **1982**, *47*, 2886.

(11) Kayser, M. M.; Morand, P. *Can. J. Chem.* **1981**, *59*, 2457. Kayser, M. M.; Eisenstein, O. *Can. J. Chem.* **1978**, *56*, 1524.

(12) Kilb, R. W.; Lin, C. C.; Wilson, E. B., Jr. *J. Chem. Phys.* **1957**, *26*, 1695.

(13) For a review see: Suter, U. *J. Am. Chem. Soc.* **1977**, *101*, 6481.

(14) Wiberg, K. B.; Squires, R. R. *J. Am. Chem. Soc.* **1979**, *101*, 5512.

(15) Wiberg, K. B.; Squires, R. R. *J. Am. Chem. Soc.* **1981**, *103*, 4473.

(16) Wiberg, K. B.; Martin, E. J.; Squires, R. R. *J. Org. Chem.* **1985**, *50*, 4717.

The heats of hydrolysis of a series of these compounds were measured. Increased steric interaction in the *gem*-dimethoxy reactant would lead to a more exothermic (less endothermic) reaction. The expected trend was found with acetals and ortho esters substituted with *n*-propyl and isopropyl groups, but the effect on the hydrolysis of ketals was in the opposite sense (energies in calories/mole):
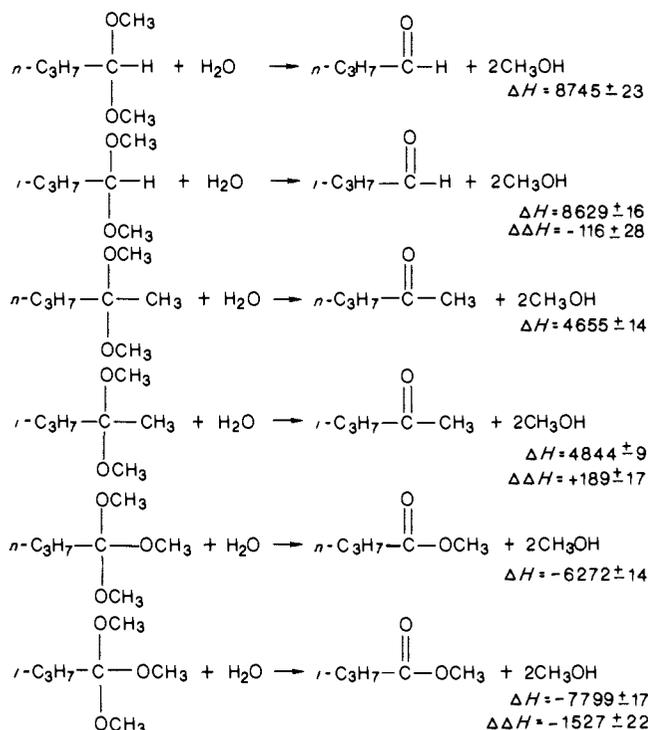
The small effect observed with the acetals is expected since with a hydrogen attached to the reaction site, conformations are available which will avoid large steric interactions with the alkyl group. With the ortho esters, no conformations are available which would minimize steric interactions, and here, a large effect of replacing *n*-propyl with isopropyl is observed.

In the case of the ketals, one again would expect relatively large steric interactions between the alkyl substitutent and the ketal group. The reversed direction of the energy change would then require that the ketones be destabilized to a greater extent than are the ketals when *n*-propyl is replaced by isopropyl. What is

Table II. 3-Fold Barriers to Rotation

compd	barrier, kcal/mol[a]	compd	barrier, kcal/mol[a]
$CH_3—CH_3$	2.85	$CH_3—COCl$	1.35
$CH_3—CH=CH_2$	2.00	$CH_3—CO_2H$	0.48
$CH_3—CH=O$	1.17	$CH_3—NO_2$	0.006[b]
$CH_3—COCH_3$	0.76		

[a] Krisher, L. C.; Saegebarth, E. *J. Chem. Phys.* **1971**, *54*, 4553. Wilson, E. B., Jr. *Adv. Chem. Phys.* **1959**, *2*, 367. [b] 6-fold barrier.

Table III. Rotational Barrier for Propionic Acid[a]

conformer	3-21G E	3-21G ΔE	6-31G*[b] E	6-31G*[b] ΔE
eclipsed (0°)[c]	−265.356 79	0.00	−266.843 94	0.00
gauche (60°)	−265.353 02	2.27	−226.842 14	1.13
skew (120°)	−265.354 93	1.14	−266.842 38	0.97
trans (180°)	−265.353 34	2.10	−266.841 28	1.67

[a] The total energies are given in hartrees (1 hartree = 627.5 kcal/mol), and the energy differences are given in kcal/mol. [b] Calculated at the 3-21G optimized geometry. [c] Nominal angles. The calculated angles are given in Table IV.

Table IV. Structural Data for Propionic Acid (3-21G)[a]

unit	conformer e	conformer g	conformer s	conformer t
$\tau_{4,1,2,3}$	0.00 (0.00)	76.	121.28	180.00
$\tau_{4,1,2,7}$	122.66	−162.39	−119.22	−56.71
$\tau_{4,1,2,8}$	122.66	−42.93	−0.97	56.71
$r_{C=O}$	1.202 (1.209 ± 0.009)	1.204	1.202	1.204
$r_{C—O}$	1.359 (1.364 ± 0.012)	1.358	1.361	1.356
$r_{O—H}$	0.969	0.969	0.968	0.969
$r_{1,2}$	1.501 (1.515 ± 0.030)	1.502	1.499	1.508
$r_{2,3}$	1.532 (1.540 ± 0.030)	1.548	1.545	1.532
$r_{2,7}$	1.084 (1.123 ± 0.040)	1.078	1.083	1.085
$r_{2,8}$	1.084	1.082	1.079	1.085
$\angle4,1,2$	126.94 (126.7 ± 2.4)	126.31	127.68	125.49
$\angle4,1,5$	122.14	121.95	121.81	121.66
$\angle2,1,5$	110.91 (111.2 ± 2.4)	111.74	110.51	112.86
$\angle1,2,3$	111.44 (112.8 ± 3 0)	109.69	110.71	114.49
$\angle1,2,7$	107.65	109.15	107.99	106.78
$\angle1,2,8$	107.65	107.93	108.09	106.78

[a] Units: Å and deg. The experimental data from ref 20 are given in parentheses.

the origin of the ketone destablization by an isopropyl group, and why is it not also found with esters?

In an effort to understand these energy changes and to cast some light on the conformations of α-substituted ketones and their energies, we have initiated a series of calculations of the barriers to rotation for isopropyl groups attached to carbonyl groups. In a study of methyl and ethyl substituents, we found that the experimental barriers could be well reproduced by these calculations.[17] The use of the 3-21G basis set for the geometry optimizations led to structures which were in good accord with the experimental data. In order to reproduce the observed energy differences, it was necessary to use the 6-31G* basis set. Electron correlation contributed only a small amount to the calculated barriers.

Before we proceeded to the isopropyl-substituted compounds, it appeared desirable to briefly study acetic acid and propionic acid to serve as models for interpreting the results for the butyric acids. Geometry optimization was performed by using both the 3-21G and 6-31G* basis sets for acetic acid (Table I). Whereas for acetaldehyde, acetone, and propene the barrier was calculated satisfactorally by using any basis set, in the case of acetic acid the 3-21G basis gave too large a barrier. The barrier calculated by using the 6-31G* basis was quite satisfactory. The low barrier for acetic acid is interesting and is compared with the barriers for other compounds with methyl rotors in Table II. A simple interpretation is that the two oxygens are not greatly different, and so the barrier begins to approach a 6-fold barrier as seen with nitromethane. The latter type of barrier is invariably small.[18]

The calculated energies for the conformers of propionic acid are shown in Table III, and the structures are given in Table IV. The 3-21G relative energies and structures agree well with those reported by Siam et al.[19] using the 4-21G basis set. As we have observed in other cases,[17] the relative energies of the rotamers change considerably on going to the more flexible 6-31G* basis set. The structure of the lower energy eclipsed conformer has been determined via microwave spectroscopy,[20] and our calculated structure is in very good accord with these data. The barrier has not been determined experimentally, but in view of the generally good agreement between the 6-31G* relative energies and ex-
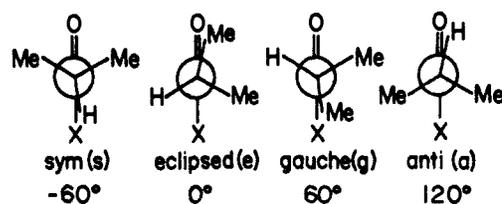
perimental results found in similar cases,[17] the calculated values are probably fairly reliable.

The conformations which were considered for the isopropyl-substituted compounds are

sym (s)　　eclipsed (e)　　gauche (g)　　anti (a)
−60°　　　　0°　　　　　　60°　　　　　120°

Here, X = H, CH_3, and OH. We shall make the assumption that OH will be an appropriate surrogate for a OCH_3 and that conformational effects in carboxylic acids and esters will be essentially the same.

The energy minimization is readily effected for the s and a conformers since they are defined by symmetry. The eclipsed conformer represented a minimum in each case and thus could easily be located. The gauche conformers provided the only difficulty since they neither represent minima nor are defined by symmetry. The energies of several conformers near the expected gauche torsional angle (60°) were calculated, and the angle corresponding to the maximum energy was determined by using a parabolic fit.

The calculations were carried out by using the split-valence 3-21G basis set which has been found to give structures for related compounds which are in good agreement with the experimental data. It was found in other cases that polarization functions are important in calculating the relative energies of conformers. Therefore, the energies were calculated by using the 6-31G* basis set and the 3-21G geometries. The energies are summarized in Table V, and the structures are given in Table VI.

The heats of formation of *n*-butyraldehyde and isobutyraldehyde have been determined via oxygen bomb calorimetry, and the latter was found to be 2.8 ± 0.5 kcal/mol more stable than the former.[21] This is in accord with the general observation that branched isomers are normally more stable than the linear isomers.[22] However, with *n*-propyl methyl ketone and isopropyl methyl ketone, the observed heats of formation differ only by 0.5 ± 0.3

(17) Wiberg, K. B.; Martin, E. J. *J. Am. Chem. Soc.* **1985**, *107*, 5035.

(18) Wilson, E. B., Jr. *Adv. Chem. Phys.* **1959**, *2*, 367.

(19) Siam, K.; Klimkowski, V. T.; Ewbank, J. D.; Schafer, L.; Van Alsenoy, C. *J. Comput. Chem.* **1984**, *5*, 451. The relative energies of the isobutyric acid conformers also are reported therein but do not agree with the present results.

(20) Callomon, J. H.; Hirota, E.; Kuchitsu, K.; Lafferty, W. J.; Maki, A. G.; Pote, C. S. *Landolt-Börnstein*; Springer-Verlag: Berlin, 1976; New Series, Group II, Vol. 7.

(21) Cox, J. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Academic: London, 1970.

(22) Neopentane is 5 kcal/mol more stable than *n*-pentane, and 2,2,3,3-tetramethylbutane is the most stable of the octane.[21]

Table V. Calculated Energies for n-Propyl- and Isopropyl-Substituted Compounds[a]

R	conf[b]	3-21G		6-31G*		$\Delta\Delta H_f$(est)	$\Delta\Delta H_f$(obsd)
		E	ΔE	E	ΔE		
a. Aldehydes							
n-Pr	e	-229.696 95	1.52	-230.985 78	0.03	1.8	2.8 ± 0.5
i-Pr	s(-60°)	-229.695 81	2.24	-230.982 88	1.79		
	e(0°)	-229.699 38	0.00	-230.985 74	0.00	0.0	0.0
	g(60°)	-229.695 77	2.27	-230.983 07	1.68		
	a(120°)	-229.697 07	1.45	-230.984 58	0.73		
b. Ketones							
n-Pr	e	-268.528 47	0.48	-270.031 66	-1.27	0.5	0.5 ± 0.3
i-Pr	s(-60°)	-268.528 64	0.37	-270.029 76	-0.07	0.0	0.0
	e(0°)	-268.529 24	0.00	-270.029 64	0.00		
	g(60°)	-268.524 49	2.98	-270.026 85	1.75		
	a(120°)	-268.525 67	2.24	-270.027 82	1.14		
c. Acids							
n-Pr	e	-304.176 04	1.86	-305.878 98	-0.53	1.2	
i-Pr	s(-60°)	-304.176 27	1.73	-305.877 64	0.30		
	e(0°)	-304.179 02	0.00	-305.877 37	0.00	0.0	
	g(60°)	-304.175 34	2.33	-305.876 10	1.27		
	a(120°)	-304.177 59	0.90	-305.876 75	0.87		
n-butane		-156.432 47	1.26	-157.298 40	0.36	(2.1)	2.1
isobutene		-156.434 47	0.00	-157.298 97	0.00	0.0	0.0

[a] The total energies are given in hartrees (1 hartree = 627.5 kcal/mol), and the energy differences are given in kcal/mol. [b] Nominal torsional angles are given here. The calculated angles are given in Table VI. [c] Estimated from the calculated energy differences where R = n-propyl and isopropyl and a 1.75 kcal/mol correction for changes in correlation energy and zero-point energy found with n-butane/isobutane.

kcal/mol.[21] It is known that part of the energy difference between branched and unbranched isomers results from electron correlation and that part is due to zero-point energy differences.[23] These two factors should not be strongly influenced by substituents. Therefore, we assume that the correction for these terms will be the same for isobutane and butane as for the compounds in Table I. This allows the energy differences to be estimated from the calculated total energies, giving a 1.8 kcal/mol difference for the aldehydes and 0.5 kcal/mol difference for the ketones. These values are in reasonable agreement with the experimental results. It might be noted that the experimental enthalpy difference for the aldehydes is larger than found with other cases of chain branching, and the lower end of the range (i.e., 2.3 kcal/mol) may be the better experimental value. Unfortunately, an experimental value for the difference in ΔH_f between butyric acid and isobutyric acid is not available, but the difference is predicted to be about 1.2 kcal/mol, which is somewhat smaller than that found for the aldehydes. These results are in complete agreement with the energy changes observed in our study of the hydrolysis of acetals, ketals, and ortho esters and show that the replacement of n-propyl by isopropyl leads to a normal change in energy for aldehydes and acids, but with the methyl ketones there is some factor which leads to significant destabilization (~ 1 kcal/mol) with the isopropyl substituent. We should like to understand the origin of this destabilization.

We have shown in the case of propionaldehyde that the attractive interaction between the alkyl group and the carbonyl may be described as a dipole-induced dipole interaction.[17] This involves the mixing of the ethyl group C–C σ^* bond orbital with the σ bond orbital in the presence of the carbonyl dipole, leading to a polarization of the C–C bond and an attractive interaction. Evidence for this interaction was (a) the importance of polarization functions at carbon in reproducing the experimental barriers, (b) the observation of charge shifts in electron density plots which correspond to the above interaction, and (c) the absence of a corresponding stabilization of the conformer with the alkyl group eclipsed with a carbon–carbon double bond in compounds such as 1-butene. With a methyl ketone (i.e., 2-butanone), an additional repulsive interaction was found when the alkyl group had a torsional angle
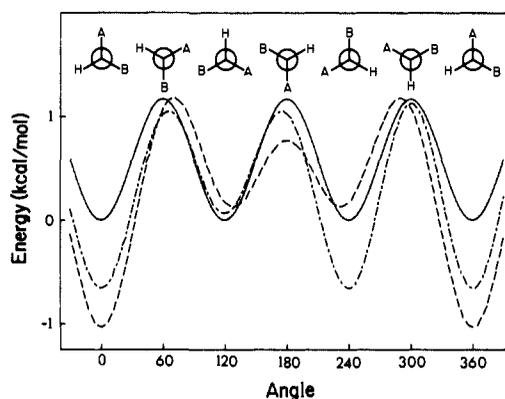
(23) The differences in energy between isobutane and n-butane and between neopentane and n-pentane are well reproduced by ab initio calculations using 6-31G* basis set and electron correlation (MP3) along with correction for the difference in zero-point energies (unpublished calculations). Cf.: Pitzer, K. S.; Catalano, E. *J. Am. Chem. Soc.* **1956**, *78*, 4844.

Figure 1. Rotational barriers for acetaldehyde (solid line, A = B = H), propionaldehyde (dashed line, A = CH₃, B = H), and isobutyraldehyde (dot-dashed line, A = B = CH₃). In each case, for the Newman projections, the carbonyl is up and the aldehyde hydrogen is down. Note that the curves are similar to that for acetaldehyde except when a methyl is eclipsed with the carbonyl.
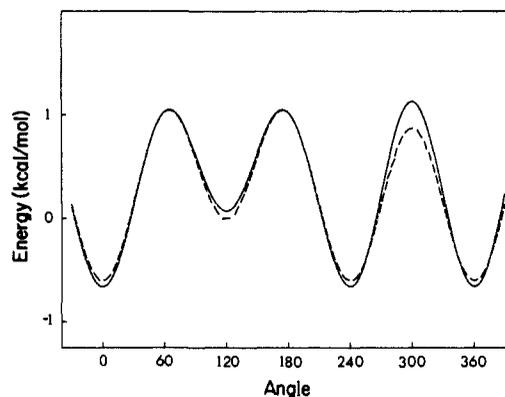

Figure 2. Rotational barrier for isobutyraldehyde (solid line) compared with the sum of the 3-fold acetaldehyde barrier and $-0.6(\cos^2 \theta)$ for ±90° from a methyl eclipsed with the carbonyl.

of 60° to the ketone methyl (gauche methyl–methyl interaction) or an angle of 0° (eclipsed methyl–methyl interaction). The interaction was observed in the energies of these conformers, as well as in their bond angles.

Table VI. Structural Data for Isopropyl Derivatives (3-21G)

unit	conformer			
	s	e	g	a
a. Isobutyraldehyde				
$\tau_{5,1,2,3}$	59.95	121.08	186.91	-119.71
$\tau_{5,1,2,4}$	-59.95	-0.71	-(64)	119.71
$\tau_{5,1,2,7}$	180.00	-121.00	-53.03	0.00
$r_{C=O}$	1.210	1.209	1.209	1.209
$r_{1,2}$	1.515	1.510	1.517	1.508
$r_{2,3}$	1.544	1.546	1.534	1.543
$r_{2,4}$	1.544	1.532	1.546	1.543
$r_{1,6}$	1.087	1.089	1.089	1.090
$r_{2,7}$	1.082	1.087	1.085	1.082
$\angle 2,1,5$	122.87	124.91	123.73	125.84
$\angle 2,1,6$	116.24	114.19	115.42	113.03
$\angle 5,1,6$	120.89	120.90	120.85	121.13
$\angle 1,2,3$	108.87	107.43	110.62	108.94
$\angle 1,2,4$	108.87	110.65	108.80	108.84
$\angle 1,2,7$	109.00	107.38	107.25	107.78
b. Isopropyl Methyl Ketone				
$\tau_{6,2,3,4}$	59.94	106.45	-173.84	-118.02
$\tau_{6,2,3,5}$	-59.94	-14.89	(62)	118.02
$\tau_{6,2,3,10}$	180.00	-135.42	-53.19	0.00
$r_{C=O}$	1.212	1.212	1.213	1.213
$r_{1,2}$	1.511	1.517	1.514	1.517
$r_{2,3}$	1.523	1.521	1.536	1.521
$r_{3,4}$	1.543	1.549	1.536	1.543
$r_{3,5}$	1.543	1.534	1.547	1.543
$r_{3,10}$	1.082	1.085	1.085	1.082
$\angle 1,2,3$	116.50	116.20	119.13	117.61
$\angle 6,2,3$	120.77	121.79	119.52	121.17
$\angle 1,2,6$	122.73	122.00	121.36	121.22
$\angle 2,3,4$	108.82	109.20	115.11	111.30
$\angle 2,3,5$	108.82	110.35	107.86	111.30
$\angle 2,3,10$	109.46	108.18	109.17	105.31
c. Isobutyric Acid				
$\tau_{5,1,2,3}$	60.01	0.34	(-65)	-118.99
$\tau_{5,1,2,4}$	-60.01	-122.20	171.26	118.99
$\tau_{5,1,2,8}$	180.00	119.91	50.32	0.00
$r_{C=O}$	1.204	1.203	1.205	1.203
r_{C-O}	1.356	1.359	1.356	1.362
r_{O-H}	0.969	0.970	0.969	0.968
$r_{1,2}$	1.504	1.509	1.509	1.502
$r_{2,3}$	1.542	1.535	1.547	1.542
$r_{2,4}$	1.542	1.547	1.531	1.542
$r_{2,8}$	1.078	1.084	1.084	1.080
$\angle 2,1,5$	125.48	126.72	124.96	127.64
$\angle 2,1,6$	112.51	112.23	113.50	110.78
$\angle 5,1,6$	122.01	121.05	121.54	121.58
$\angle 1,6,7$	111.60	111.11	111.49	111.73
$\angle 1,2,3$	108.47	110.25	107.69	109.37
$\angle 1,2,4$	108.47	110.01	113.10	109.37
$\angle 1,2,8$	108.00	107.03	105.85	106.62

Figure 3. $-(\cos^2 \theta)$ methyl–carbonyl eclipsed interaction given by the solid line, A. The 1- and 2-fold components (B and C) are given by the dashed lines, and their sum (D) is given by the dot-dashed line.

Figure 4. Rotational barrier for acetic acid (solid line, A = B = H), propionic acid (dashed line, A = CH_3, B = H), and isobutyric acid (dot-dashed line, A = B = CH_3). In each case, for the Newman projections, the carbonyl is up and the hydroxy group is down. The interaction terms are A, dipole-induced dipole stabilization; B, gauche methyl–hydroxy interaction; and C, cis methyl–hydroxy interaction.

The torsional barriers for acetaldehyde, propionaldehyde, and isobutyraldehyde are shown graphically in Figure 1. Here, the relative energies for the 300° conformers were arbitrarily set to be equal since the differences between compounds should be minimized in this case. It can be seen that all three compounds are subject to a 3-fold barrier with about the same height and that the propionaldehyde and isobutyraldehyde conformers having a methyl group eclipsed with the carbonyl are stabilized by about 1 kcal/mol. The above analysis suggests that the angular dependence should be $\cos^2 \theta$, which is appropriate for a dipole-in-
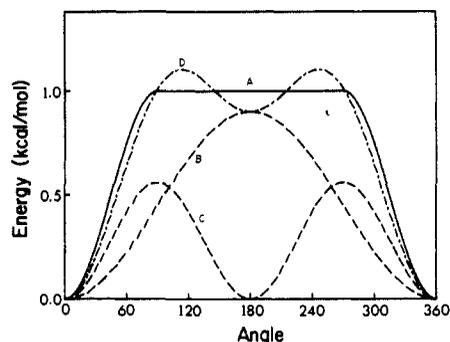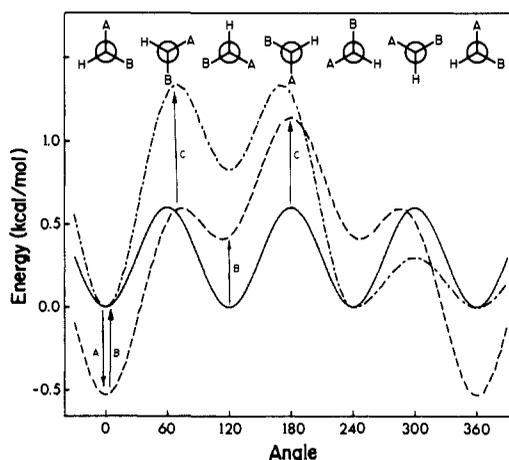
duced dipole interaction.[24] The calculated barrier for isobutyraldehyde is compared in Figure 2 with that derived by using the 3-fold barrier found for acetaldehyde along with a $-(\cos^2 \theta)$ interaction between a C-methyl group and the carbonyl. The fit is quite good.

The interaction function between the carbonyl and the methyl group (i.e., $\cos^2 \theta$) is shown as the solid line in Figure 3. Rotational barriers are commonly examined by decomposing them into 1-, 2-, and 3-fold terms,[25] and we have presented such an analysis for ethyl-substituted aldehydes and ketones.[17] However, this type of analysis may be misleading. A 1-fold barrier (dashed lines in Figure 3) does not rise rapidly enough to correspond to the experimental result. In order to provide a more rapid rise in energy and to give a more level energy change between 60° and 300°, it is necessary to add a 2-fold term. The sum of the two terms is shown by the dash–dot–dash line. In this view, the 2-fold term is simply a correction to the 1-fold term and has no independent physical significance.

The barriers to rotation for the carboxylic acids are shown in Figure 4. The curves for acetic and propionic acids are placed on the energy coordinate so that the 300° conformations which should have minimum interactions involving the methyl group would have about the same energy. The curve for isobutyric acid was placed so as to reproduce the $\sim$0.6 kcal/mol destabilization noted above. The barrier for propionic acid can be seen to have

(24) The dipole induced into the C–C bond by the carbonyl has a $\cos \theta$ dependence. The interaction between the induced dipole and the carbonyl dipole also has a $\cos \theta$ dependence, leading to a $\cos^2 \theta$ function.

(25) Radom, L.; Hehre, W. J.; Pople, J. A. *J. Am. Chem. Soc.* **1972**, *94*, 2371. Jeffrey, G. A.; Yates, J. H. *Ibid.* **1979**, *101*, 820. Bartell, L. S. *Ibid.* **1977**, *99*, 3279. Allinger, N. L.; Hindman, D.; Hönig, H. *Ibid.* **1977**, *99*, 3282.
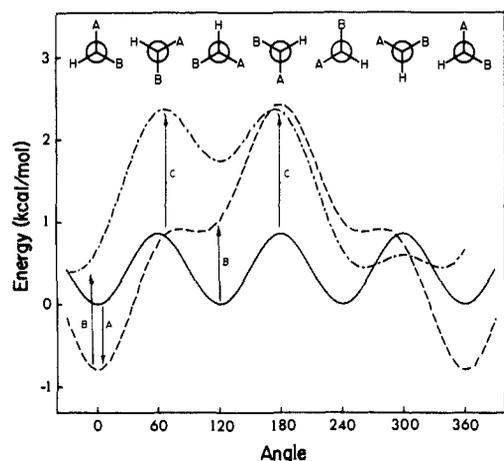
Figure 5. Rotational barriers for acetone (solid line, A = B = H), methyl ethyl ketone (dashed line, A = CH_3, B = H), and isopropyl methyl ketone (dot-dashed line, A = B = CH_3). In each case, for the Newman projections, the carbonyl is up and the methyl is down. The interaction terms are A, dipole-induced dipole stabilization; B, gauche methyl–methyl interaction; and C, cis methyl–methyl interaction.

a minimum when the methyl eclipses the carbonyl and a maximum when the methyl is trans to the carbonyl. The latter must result from a repulsive interaction between the methyl and the hydroxy group and may also be seen in the considerably increased C_1–C_2–C_3 bond angle in the trans conformer (114.5°) vs. the eclipsed conformer (111.4°, Table IV). In the case of isobutyric acid, minima are found when methyl is eclipsed with the carbonyl, and maxima are found when methyl is eclipsed with the hydroxy group. The minimum for isobutyric acid has a higher energy than that for propionic acid, and this results from a gauche interaction between one of the methyl groups and the hydroxy group.

It can be seen that the interaction between the substituent and the carboxylic acid group involves the following interactions: (a) a 3-fold barrier as found with acetic acid ($\sim$0.5 kcal/mol); (b) a stabilizing interaction when a methyl is eclipsed with the carbonyl ($\sim$–0.5 kcal/mol); (c) a gauche repulsive interaction between a methyl and the hydroxy ($\sim$0.5 kcal/mol); and (d) a syn repulsive interaction between a methyl and a hydroxy ($\sim$1.0 kcal/mol).

The gauche interaction is absent in the aldehydes. As a result, the energy difference between isobutyric acid and butyric acid is less than the difference between isobutyraldehyde and butyraldehyde by the magnitude of the gauche interaction.

Finally, the barriers to rotation for the methyl ketones are shown in Figure 5. The barrier for methyl ethyl ketone resembles that for propionic acid except that the interactions are larger by a factor of about 2. This indicates that methyl–methyl interactions are energetically approximately twice as large as methyl–hydroxyl interactions. This is in accord with the difference in A values for methyl and hydroxy.[26] Again the methyl–methyl repulsion in the gauche rotamer may be seen in the calculated C–C–C angles (119.1° and 115.1°). The potential curve for methyl isopropyl ketone resembles that for isobutyraldehyde from 0° to 240°, and the interactions are again about twice as large in the former case. However, the calculations suggest that there should be a shallow minimum at about 300° (–60°) for the syn rotamer having the carbonyl between the two methyl groups. It appears to result from the destabilization of the 240° and 360° rotamers by the gauche methyl–methyl interactions.

The repulsive interactions in isopropyl methyl ketone may be seen in the changes in bond angles which occur as a result of rotation about the C–C bond. They are shown in Figure 6. The
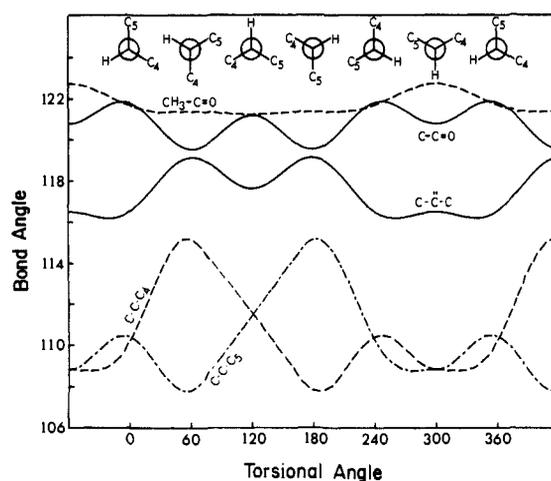

Figure 6. Changes in bond angles as a function of the torsional angle adjacent to the carbonyl group of methyl isopropyl ketone.

largest changes are found when a methyl of the isopropyl group eclipses the methyl attached to the carbonyl. However, despite the considerable gauche methyl–methyl interactions which were observed in the relative energies, no significant angular distortions are noted at 0° or 240°.

In summary, additional evidence has been presented for a dipole-induced dipole-stabilizing interaction between an alkyl group and a carbonyl. This is opposed in many cases by gauche or syn interactions between the alkyl group and the other substituent at the carbonyl. It is interesting to note that the results of this investigation has been used by Still[27] to reparameterize the MM2[28] torsional parameters and that these new parameters correctly reproduce the observations of Goldsmith[27] on the relative energies of the 5,10-dimethyldecalin-1,4-dione conformers, whereas the standard parameters do not.

It now remains to examine unsymmetrical cases and substituent groups containing carbon–carbon double bonds. The latter (such as a phenyl) frequently leads to markedly increased stereoselection in carbonyl addition reactions as compared to an alkyl group,[29] and this may result from a ground-state conformational effect which persists in the activated complex or from some interaction unique to the latter. The origin of the gauche methyl–methyl and methyl–hydroxy destabilizing interactions remains to be determined here and in other cases such as *n*-butane. It does not appear to be just a simple repulsive interaction in view of the small angular distortions which were found. The barrier to rotation about the C–O single bond of the acids and esters also requires study. These aspects of the rotational barriers are presently under investigation and will be reported at a later time.

Registry No. Acetaldehyde, 75-07-0; propionaldehyde, 123-38-6; isobutyraldehyde, 78-84-2; acetic acid, 64-19-7; propionic acid, 79-09-4; isobutyric acid, 79-31-2; acetone, 67-64-1; methyl ethyl ketone, 78-93-3; isopropyl methyl ketone, 563-80-4.

(26) Jensen, J. R.; Bushweller, C. *Adv. Alicyclic Chem.* **1971**, *3*, 139.

(27) Goldsmith, D. J.; Bowen, J. P.; Quamhiyeh, E.; Still, C., unpublished results.
(28) Burkert, U.; Allinger, N. L. *Molecular Mechanics*; ACS Monograph 177; American Chemical Society: Washington, D.C., 1982.
(29) Cram, D. J.; Abd Elhafez, F. A. *J. Am. Chem. Soc.* **1952**, *74*, 5828.
(30) Binkley, J. S.; Frish, M. J.; De Frees, D. J.; Raghavachari, K.; Whiteside, R. A.; Schlegel, H. B.; Fluder, E. M.; Pople, J. A. GAUSSIAN 82, Department of Chemistry, Carnegie-Mellon University, 1980.