

Molecular Mechanics (MM3) Studies of Carboxylic Acids and Esters[†]

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Abstract: Force field calculations using MM3 have been extended to include carboxylic acids and esters. Accurate structures for several small molecules were well reproduced, and vibrational spectra moderately so. Available thermochemical data were examined. A good portion of them were rejected as inaccurate, and the remainder were fit.

Introduction

Force field calculations are now a standard way to obtain a great deal of information about molecules rather quickly and easily.¹ The MM3 force field for hydrocarbons was reported in 1989² and has subsequently been extended to several classes of functionalized molecules.³ The extension here is continued to the carboxylic acid class, and also to esters.

More or less accurate electron diffraction and/or microwave structural data are available for a number of relatively small molecules of this class. Additionally, vibrational spectroscopic data are also available for these compounds, as are heats of formation. The basic approach then is to develop a force field which fits these available data, and which is consistent with the MM3 force field as previously described in the literature. While this would be straightforward if there were sufficient accurate data available, the data available are not always sufficient for each particular item of interest, nor is the accuracy always adequate.

Wiberg and co-workers⁴ recently published a paper in which they reported some thermochemical studies on esters, and also some MM3 calculations.⁴ They did not make it clear in the paper, and we hasten to do so here, that the parameters in the MM3(90) program for esters all are accompanied by ** in the left margin, which indicates these are only preliminary parameters. For the most part, they are simply MM2 parameters, carried over to the MM3 force field. Many people currently engaged in molecular modeling are studying such things as the docking of small molecules into protein receptors, and for such purposes, errors of 0.02 Å in a bond length, or 3° in a bond angle, will be of no consequence. However, the MM3 force field has a potential accuracy much greater than this. The paper by Wiberg therefore attributes various inaccuracies to MM3 calculations of esters, but these are mainly due to the fact that the MM3 parameterization for this class of compounds had not yet been worked out. As will be shown herein, essentially all of his stated inaccuracies disappear when the true MM3 force field is used for the calculations.

Results and Discussion

The MM3 parameter set devised for acids and esters is shown in Table I. Parameters not given here, but required for the molecules under discussion, come from the force field on hydrocarbons,² or else from the force field on aldehydes and ketones,^{3b} and are carried over from those works. All additional parameters which had to be derived for calculations in the present work are included in Table I. It is emphasized that the MM3 force field contains quite a few terms in addition to the quadratic ones. Also, there are various cross terms (such as stretch-bend interactions) in this force field. With the aid of these additional terms, one can obtain better approximations to the structures of these molecules than was possible earlier.

Some discussion of atom types is required at this point. It was clear long ago that one cannot simply specify an element in molecular mechanics calculations, because the parameters (stretching constants, for example) depend on whether we are

talking about a single bond, or a double bond, or a triple bond to that element. Hence atom type numbers were introduced into our force fields in 1967. Type 1 is a saturated carbon, type 2 is an olefinic carbon, type 3 is a carbonyl carbon, type 7 is a carbonyl oxygen, and so on. These atom types proved to be quite useful, and their properties proved to be transferable to a surprisingly high degree. Indeed, if we wish to calculate the bond lengths of carbonyl bonds for a wide variety of compounds (ketones, esters, acid chlorides, amides, etc.), we can do so with a single transferable set of stretching parameters. Thus as one goes through this whole series, the variation in the bond lengths of the carbonyl bonds is of the order of 0.007 Å. Taking some average value gives the bond lengths mostly within about 0.003 Å, which is the approximate experimental error. As far as structure, then, one can use only a few atom types for a wide variety of molecules.

Unfortunately, this highly general transferability of parameters is only an approximation, and for spectroscopic purposes, not a very good approximation. Thus it has long been known that the classes of compounds listed above show systematic variations in their carbonyl stretching frequencies. The stretching frequency of an ester is typically about 30 cm⁻¹ greater than that of a ketone, which is greater than that of an amide, and so on. While the variations in structure with compound class are small, by the standards of accuracy that we apply to structure, the spectroscopic errors that result if one uses one general overall stretching constant for carbonyl bonds are too large to be acceptable. These 30-cm⁻¹ differences in stretching frequencies are highly characteristic of the particular class of compound under examination. They do not stem from mass differences, and hence are due to differences in stretching constants as a function of compound class. These differences are very practically useful. So we might say that, to the first approximation, a carbonyl group is a carbonyl group, be it a part of a ketone, ester or whatever. But if we really want to be able to accurately calculate vibrational spectra (let's say to within 10 cm⁻¹ or so), we have to have different stretching constants for these different classes of carbonyl bonds. Unfortunately,

(1) Burkert, U.; Allinger, N. L. *Molecular Mechanics*; American Chemical Society: Washington, DC, 1982.

(2) Allinger, N. L.; Yuh, Y. H.; Lii, J.-H. *J. Am. Chem. Soc.* **1989**, *111*, 8551, 8566, 8576. The MM3 program is available to all users from the Technical Utilization Corp. Inc., 235 Glen Village Court, Powell, Ohio 43065, and to commercial users only from Tripos Associates, 1699 South Hanley Rd, St. Louis, MO 63144, and to academic users only from the Quantum Chemistry Program Exchange, University of Indiana, Bloomington, IN 47405. The current version is available to run on most types of computers, and interested parties should contact one of the distributors directly.

(3) (a) Allinger, N. L.; Rahman, M.; Lii, J.-H. *J. Am. Chem. Soc.* **1990**, *112*, 8293. (b) Schmitz, L. R.; Allinger, N. L. *J. Am. Chem. Soc.* **1990**, *112*, 8307. (c) Allinger, N. L.; Li, F.; Yan, L. *J. Comput. Chem.*, **1990**, *11*, 848. (d) Allinger, N. L.; Li, F.; Yan, L.; Tai, J. C. *J. Comput. Chem.* **1990**, *11*, 868. (e) Allinger, N. L.; Kuang, J.; Thomas, H. *J. Mol. Struct. (THEOCHEM)* **1990**, *209*, 125. (f) Lii, J.-H.; Allinger, N. L. *J. Comput. Chem.* **1991**, *12*, 186. (g) Allinger, N. L.; Chen, K.; Rahman, M.; Pathiaseril, A. *J. Am. Chem. Soc.* **1991**, *113*, 4505. (h) Aped, P.; Allinger, N. L. *J. Am. Chem. Soc.* **1992**, *114*, 1. (i) Allinger, N. L.; Quinn, M.; Rahman, M.; Chen, K. *J. Phys. Org. Chem.* **1991**, *4*, 647. (j) Chen, K.; Allinger, N. L. *J. Phys. Org. Chem.* **1991**, *4*, 659.

(4) (a) Wiberg, K. B.; Waldron, R. F.; Schulte, G.; Saunders, M. *J. Am. Chem. Soc.* **1991**, *113*, 971. (b) Wiberg, K. B.; Waldron, R. F. *J. Am. Chem. Soc.* **1991**, *113*, 7697.

[†] Mainly abstracted from the thesis submitted to the University of Georgia as partial fulfillment of the requirements for the Master's degree by Z.S.Z., Aug 1991.

Table I. The MM3 Parameter Set for Carboxylic Acids and Esters

1. Atom Type												
type	atom	description			type	atom	description			type	atom	description
1	C	C-sp ³			24	H	COOH carboxyl			56	C	C-sp ³ (cyclobutane)
3	C	C-sp ²			75	O	C-O-H, C-O-C carboxyl			58	C	C=O (cyclobutanone)
5	H	except on N, O, S			77	O	=O, acid carbonyl			78	O	=O, ester carbonyl

2. Torsional Parameters															
no.	angle				V ₁	V ₂	V ₃	no.	angle				V ₁	V ₂	V ₃
	5	3	75	24	-0.30	5.39	0.00	4	56	56	58	75	0.20	0.400	0.00
	1	3	75	24	0.00	5.39	0.23	4	58	75	56	58	0.20	0.400	0.00
	77	3	75	24	-1.20	5.39	0.40	4	75	56	56	58	0.20	0.000	0.18
	5	3	75	1	-0.30	7.50	0.00	1	56	56	58	58	0.00	0.000	0.18
	78	3	74	1	-2.66	7.50	0.20	58	75	56	58	58	1.25	0.44	0.00
	1	3	75	1	1.05	7.50	-0.20	5	1	75	3	3	0.10	0.00	0.00
5	1	3	75	1	1.55	6.00	0.00	5	1	3	75	75	0.25	0.85	0.00
4	56	75	58	56	-1.77	6.00	0.00	1	1	3	75	75	0.55	1.550	0.10
	56	75	58	77	-2.66	7.50	0.20	5	1	1	3	75	1.05	1.106	0.00
	58	75	56	58	0.0	0.0	0.001	1	1	75	3	3	-2.28	1.000	0.00
	5	56	58	75	0.0	0.0	0.000	5	1	1	75	3	1.05	0.440	0.00

3. Stretching Parameters														
no.	bond		K _s (mdyn/Å)	l ₀ (Å)	no.	bond		K _s (mdyn/Å)	l ₀ (Å)	no.	bond		K _s (mdyn/Å)	l ₀ (Å)
	3	75	6.00	1.3538	4	56	75	5.70	1.4250	3	78	78	9.80	1.2140
5	1	75	5.70	1.4160		24	75	7.15	0.9737	3	5	5	4.64	1.1080 ^a
5	3	75	5.80	1.3550		3	77	9.80	1.2140	58	78	78	10.50	1.1678
4	58	75	5.80	1.4178						1	75	75	5.70	1.4130

4. Electronegativity Corrections									
bond		end atom	electronegative/positive atom attached	correction (Å)	bond		end atom	electronegative/positive atom attached	correction (Å)
1	3	3	75	-0.022	56	58	58	75	0.004
3	75	75	24	0.015	1	5	1	75	-0.005
3	75	3	5	-0.022	1	5	1	3	-0.009
1	75	75	3	0.022	5	56	56	58	-0.006
56	75	75	58	-0.046	5	56	56	75	-0.006

5. Bond Dipole Moment Parameters							
bond		dipole moment (D)		bond		dipole moment (D)	
	3	75	0.12	5	1	75	1.47
	1	75	1.77	4	58	75	-0.12
	3	5	-1.10 ^a	4	56	75	1.87
5	3	75	-0.12		24	75	1.31
					58	78	1.86
					3	77	1.86
					3	78	1.86

6. Bending Parameters											
angle			K _θ (mdyn/deg)	θ ₀ (deg)	angle			K _θ (mdyn/deg)	θ ₀ (deg)		
3	75	24	0.69	107.7	4	56	56	75	0.34	109.0	3
75	3	77	1.70	121.5	1	75	58	78	1.00	126.0	
75	3	77	1.70	122.5	2	5	3	75	0.71	107.0	
1	75	3	1.25	112.8		1	3	75	1.55	110.3	
5	1	75	1.55	111.2	5	1	3	75	1.15	111.0	
	3	75	1.25	110.8		3	75	75	1.70	0.0	
4	56	75	1.10	99.3		58	75	78	0.80	0.0	
4	56	58	0.60	112.5		75	3	78	1.70	121.5	1
4	56	56	0.34	108.4	1	75	3	78	1.70	122.5	2
4	56	56	0.34	108.4	2	58	78	78	0.85	0.0	

7. Hydrogen Bonding Parameters							
atom types		ε	r*	atom types		ε	r*
24...77		4.950	1.830	24...75		1.450	2.140

8. Heat of Formation Parameters							
bond structure feature		normal	strainless	bond structure feature		normal	strainless
C-O in esters and acids		-37.376	-39.934	O-H (75-24)		-28.487	-27.823
H-C-O (5-3-75)		2.409	1.157				

^aParameters for acids and esters only, not for aldehydes.

when generalized, this leads to the conclusion that we need an enormous number of atom type numbers, with the same atom having a different number in each chemically distinct class of

compounds. This in turn could lead to an enormous problem in parameterization, if each and every class of compounds has to have all of its parameters determined independently from those

of the corresponding atoms in slightly different classes of compounds.

Currently it seems that some compromise is possible in the above problem. What we have chosen to do is assign different atom types to the oxygen in each of the classes of compounds indicated. By doing this, a ketone oxygen, for example, remains type 7, while an ester carbonyl oxygen becomes type 78. We can now assign different stretching parameters (and different values for l_O) to these two different kinds of oxygens. Similarly, amides, acid chlorides, etc., each have their own atom type number for the oxygen, and correspondingly their own stretching constants and values for l_O . Most of the parameters, however, remain the same for all of these different kinds of oxygens. Only the stretching parameters vary systematically sufficiently so that we want to take them into account in the spectroscopic calculations. The bending, torsion, van der Waals, etc., parameters all are the same as far as we know, to a sufficiently good approximation to fit anything we have so far examined.

What we have done, therefore, is to arrange a hierarchical system which works in the following way. When the program finds an atom type (78), it looks up in the table all of the parameters that it can find for type 78, and utilizes them in the ongoing calculation. However, it will find very few, only the stretching parameters in this case. It then looks at the hierarchical structure and finds that type 78 defaults to type 7, whereupon it uses parameters from type 7 for everything else.

With this kind of a hierarchical structure in the program, we can change those few parameters which need to be changed to obtain spectroscopic accuracy, but everything else defaults back to where it was before. We do not then have to face the problem of an infinitely expanding parameter set.

When the above atom type problem is generalized, one obtains a vastly expanded number of atom types. This brings up two new problems. One is that too much burden is placed upon the user to keep these types all properly sorted out, and always pick the right one. Accordingly, the program has been redesigned to investigate the structure, not only the atoms bound together but also their environments, and then choose the appropriate atom types for assignment to each atom. This removes the burden from the user, and the program works quickly and accurately. Finally, we, and others, have vast assemblages of input decks, with the old atom type numbers assigned. Accordingly, the old assignments of atom type numbers are initially ignored by the program, and new assignments are made from the structure and the environment. The assignments actually input are then checked, and any disagreements are noted. The user may override the program and insist upon using any desired atom types. However, the default is for the program to reassign these, ask for the user's approval, and continue. The output deck obtained after the calculation has the correct new atom types, so that the problem does not arise from then on. Hence one may use pre-existing input decks, and obtain the same results as would be obtained with proper input decks.

Finally, there is no need to have the user assign atom types at all. The user need only tell the program what element is involved, and, from examining the environment, the program will assign the correct atom type. To summarize, the input can be simplified quite a lot, with only the element having to be specified, but pre-existing decks will continue to run.

Electrostatics is of limited importance in the case of hydrocarbons, or even in the case of a ketone. We treat electrostatics in terms of bond dipoles (for molecules which do not contain ionic charges). A ketone group has bond dipoles, which add to give the molecule a dipole moment. In MM3, we calculate dipole moments solely by bond additivities. More accurate results can be obtained if one takes into account the moments in bonds induced by the permanent moments, and calculates the dipole moment from the sum of these.⁵ In our formulation, dipoles attached to

Table II. Structural Data from Experiment and MM3 for Formic Acid^a

	exp ^b (r_g from r_a)	MM3 (r_g)	calc - exp
C-O (3-75)	1.360 (3)	1.3358	-0.024
C=O (3-77)	1.216 (3)	1.2112	-0.005
O-H (75-24)	0.983 (3)	0.9738	-0.011
H-C (5-3)	1.105 (3)	1.1051	0.000
O=C-O (77-3-75)	123.4 (5)	123.81	0.4
H-C-O (5-3-75)	114.64 (56)	112.12	-2.52
C-O-H (3-75-24)	109.68 (44)	107.25	-2.43
	exp ^b	MM3	error (%)
I_x	1.0965	1.1089	1.13
I_y	6.9610	6.9014	-0.86
I_z	8.0575	8.0103	-0.59

^aUnits: Å for bond length; deg for bond angle. ^bUnits in 10^{-39} g cm².

a common atom do not interact, so they need not be taken into account in the energetics, nor in the energy minimization process. However, in an ester, two of the bonds attached to the ester carbonyl carbon, and the alkyl oxygen bond, are dipoles not attached to a common atom, and hence they do interact and have to be included in the electrostatic energy and in the energy minimization. This interaction leads to part of the energy difference that favors the *Z* form of the ester over the *E* form.

We will first examine the carboxylic acids, beginning with formic and acetic, and then later we will examine esters and lactones.

Geometries of Carboxylic Acids and Esters

The MM3 calculated structures are comparable to gas-phase electron diffraction experimental values,¹ r_g , so we may concentrate more on comparing this kind of experimental data when we fit the structural parameters. Also, because the experimental structures were themselves derived using models, moments of inertia data are the more direct microwave quantities. Accordingly, we sacrificed fitting microwave structural data a little bit to fit the actual moments of inertia better. The acids, esters, and lactones were all optimized at the same time, although only the acids will be discussed initially. The usual procedure was followed, in that we began with a set of experimental structures and picked the necessary force field parameters to approximately fit them. We used the literature force constants as a first approximation for those parameters. After rough structures were obtained, the force constants were optimized to fit spectra, and then the geometries were reoptimized by refitting the structural parameters. The heats of formation were then calculated, and finally all of these things were optimized simultaneously.

Formic Acid. Almenningen⁶ reported an electron diffraction structure for formic acid in 1969, and Bellet and co-workers⁷ reported an r_s structure from microwave studies on isotopically substituted compounds in 1971. Since bond lengths given by microwave spectroscopy (r_o , r_s) are somewhat different than the diffraction values, we took Almenningen's values as our standard. Some bond angle data which were not available from Almenningen's data were taken from Bellet's work.⁷ The quantity obtained directly from the electron diffraction radial distribution function is r_a . The bond length directly from MM3 calculation is r_g , which is found to be typically 0.002 Å larger than r_a , by averaging over all of the molecular vibrations.¹ Table II summarizes the MM3 results and experimental data (r_a values have been converted to r_g values here) for formic acid. The experimental data are not well fit for this molecule, which is the lowest member of the carboxylic acids series and is a special case. It was considered more important to fit well the larger homologues.

The moments of inertia calculated and found for formic acid are also reported in Table II. It will be seen that the fit is fairly

(5) (a) Dosen-Micovic, L.; Jeremic, D.; Allinger, N. L. *J. Am. Chem. Soc.* **1983**, *105*, 1716. (b) Dosen-Micovic, L.; Jeremic, D.; Allinger, N. L. *J. Am. Chem. Soc.* **1983**, *105*, 1723.

(6) Almenningen, A.; Bastiansen, O.; Motzfeldt, T. *Acta Chem. Scand.* **1969**, *23*, 2848.

(7) Bellet, J.; Deldalle, A.; Samson, C.; Steenbeckelers, G.; Wertheimer, E. R. *J. Mol. Struct.* **1971**, *9*, 65.

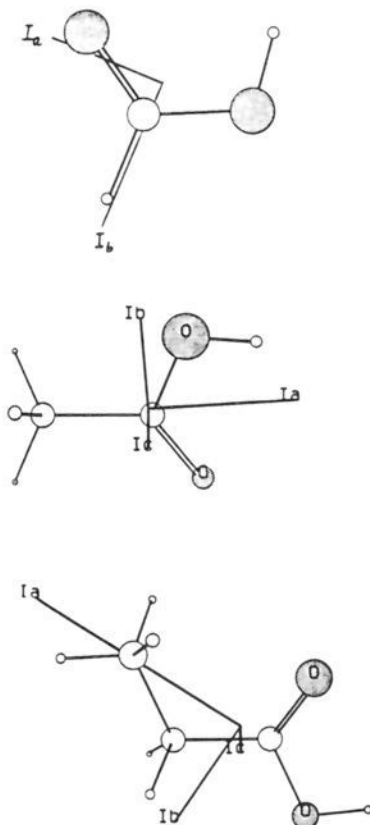


Figure 1. The MM3 structures of formic (upper), acetic (middle), and propionic acids (lower).

Table III. Structural Data from Experiment and MM3 for Acetic Acid^a

	exp ¹² (r_g)	MM3 (r_g)	calc - exp ¹²
C-O (3-75)	1.364 (3)	1.3657	0.002
C=O (3-77)	1.214 (3)	1.2126	-0.001
O-H (75-24)	0.970 ^b	0.9739	0.002
C-C (1-3)	1.520 (5)	1.4906	-0.029
O=C-O (77-3-75)	122.8 (6)	121.79	-1.0
C-C-O (1-3-75)	110.6 (6)	112.01	1.4
C-O-H (3-75-24)	107.0 ^b	107.36	0.4
C-C=O (1-3-77)	126.6 (6)	126.20	-0.4
exp ^{15,c}			
I_x	7.4034	7.4542	0.69
I_y	8.8537	8.9172	0.72
I_z	15.7598	15.8333	0.47

^aUnits: Å for bond length, deg for bond angle. ^bAssumed values. ^cUnits in 10^{-39} g cm².

poor, but trying to improve these values leads to problems with the larger molecules.

In 1959, from infrared relative intensity measurements, Miyazawa and Pitzer⁸ estimated the energy difference between the *E/Z* rotamers of this compound to be 2.0 kcal/mol. However, their conclusions were later disputed by several other experimentalists.⁹ In 1976, Hocking¹¹ reported this energy difference to be 3.90 ± 0.085 kcal/mol from microwave relative intensity measurements. Our MM3 gives a *Z* form that is 3.98 kcal/mol more stable than the *E* form, with a barrier of 12.83 kcal/mol at a O=C-O-H dihedral angle of 94.0° (4.70, 9.95 kcal/mol in MM2¹⁰), which agrees with the more recent experimental measurements.¹¹

Table IV. Structural Data from the Experiment and MM3 for Acetic Acid^a

	exp ¹⁵ (r_s)	MM3 (r_z)	MM3 - exp ¹⁵
C-O (3-75)	1.357 (5)	1.364	0.007
C=O (3-77)	1.209 (6)	1.210	0.001
OH (75-24)	0.970 (3)	0.952	-0.018
C-C (1-3)	1.494 (10)	1.489	-0.005
C-C=O (1-3-77)	126.2 (7)	126.2	-0.1
C-C-O (1-3-75)	112.0 (6)	112.0	0.0
C-O-H (3-75-24)	105.9 (5)	107.4	1.5

^aUnits: Å for bond length, deg for bond angle.

Table V. Structural Data from Experiments and MM3 for Propionic Acid^a

	exp ¹⁶ (r_g)	MM3 (r_g)	MM3 - exp
C-C (1-3)	1.518 (10)	1.4955	-0.022
C-C (1-1)	1.543 (10)	1.5279	-0.015
C=O (3-77)	1.211 (3)	1.2127	0.002
C-O (3-75)	1.367 (4)	1.3659	-0.001
C-C-O (1-3-75)	111.2 (8)	111.83	0.6
C-C=O (1-3-77)	126.7 (8)	126.61	-0.1
C-C-C (1-1-3)	112.8 (10)	112.98	0.2
O-C=O (75-3-77)	122.1 (8)	121.57	-0.5
exp ^b			
I_x	8.2637	8.2924	0.35
I_y	21.9810	22.1598	0.81
I_z	29.1882	29.3818	0.66

^aÅ for bond length, deg for bond angle. ^bUnits in 10^{-39} g cm².

Acetic Acid. From the electron diffraction patterns of the gas at 160°, Derissen¹² reported the structure for acetic acid in 1970. Table III summarizes the MM3 results and experimental data for acetic acid. Even though we fit the moments of inertia of acetic acid (Table III), the MM3 structure is quite different from Derissen's electron diffraction structure. The history of the structural investigations of acetic acid is of interest. Tabor¹³ and Caminati¹⁴ both studied the microwave structure of acetic acid (1957 and 1979, respectively), but their results differ considerably. Moreover, both structures show striking differences from the geometry derived by Derissen¹² from the electron diffraction experiment. Van Eijck et al.¹⁵ thought these differences are not surprising, as they thought that the data were quite insufficient to determine the molecular structure of acetic acid with any reliability. Hence they decided to determine the full substitution structure of this key molecule. Microwave structural data on acetic acid were reported by them in 1981.¹⁵ The MM3 calculated values were compared with their results. Unfortunately, they determined r_s values, which are the distances between the effective nuclear positions derived from isotopic differences in the rotational constants, and MM3 converts the r_g values to r_z values (but not r_s) which are the distances between average nuclear positions (in the ground vibrational state). These two kinds of values are similar but can differ by a few thousandths of an angstrom. However, this comparison is the best we can manage, and the structural data of acetic acid from experiment and from MM3 calculations are summarized in Tables III and IV. We point out that the fit of MM3 to the electron diffraction geometry by Derissen¹² is poor; this is not just the lack of resolution in the radial distribution function. The Derissen structure gives moments of inertia which are too large relative to the microwave values.

The internal rotational properties of acetic acid will be discussed along with those of methyl acetate under the latter compound.

Propionic Acid. A high-temperature gas-phase electron diffraction investigation of the structure of propionic acid has been reported by Derissen.¹⁶ Table V summarizes the structure of

(12) Derissen, J. L. *J. Mol. Struct.* **1971**, *7*, 67.

(13) Tabor, W. J. *J. Chem. Phys.* **1957**, *27*, 974.

(14) Caminati, W.; Scappini, F.; Corbelli, G. *J. Mol. Spectrosc.* **1979**, *75*, 327.

(15) Van Eijck, B. P.; Van Opheusden, J.; Van Schaik, M. M. M.; Van Zoeren, E. *J. Mol. Spectrosc.* **1981**, *86*, 465.

(8) Miyazawa, T.; Pitzer, K. S. *J. Chem. Phys.* **1959**, *30*, 1076.

(9) Wiberg, K. B.; Laidig, K. E. *J. Am. Chem. Soc.* **1987**, *109*, 5935.

(10) See ref 1.

(11) Hocking, W. H. *Z. Naturforsch.* **1976**, *31a*, 1113.

Table VI. Structural Data from the Experiment and MM3 for Propionic Acid^a

	exp ¹⁷ (r_e)	MM3 (r_z)	MM3 - exp ¹⁷
C-C (1-3)	1.509 (2)	1.493	-0.016
C-C (1-1)	1.523 (3)	1.522	-0.001
C=O (3-77)	1.210 (1)	1.210	0.000
C-O (3-75)	1.352 (2)	1.362	0.010
C-C-O (1-3-75)	111.8 (1)	111.8	0.0
C-C=O (1-3-77)	125.8 (2)	126.6	0.8
C-C-C (1-1-3)	112.7 (1)	113.0	0.3

^aUnits: Å for bond length, deg for bond angle.

propionic acid from experiment and from MM3 calculations.

It is surprising that the C-C (type 1-3) bond length in MM3 is so short, as we expect it to be a little bit longer, but still not as long as in Derissen's electron diffraction experiment. It is helpful to compare the MM3 calculated values with the most recent microwave data given by Stiefvater.¹⁷ These data are summarized in Table VI. The MM3 calculated r_z values are correct on average, in that they gave good moments of inertia. The C-C (1-3) bond is calculated too short and the C-O bond too long, but by similar amounts. This may, in fact, be an experimental problem. We note that the electron diffraction bond lengths of Derissen (both acetic and propionic acids) are systematically too long. They are inconsistent with the experimental moments of inertia. This fact suggests a calibration error in his experiments, possibly in the wave length of the electrons used.

The rotational energy curve of the ethyl group from MM3 calculation is consistent with that from the 6-31G* calculation.¹⁸

Methyl Formate and Methyl Acetate. We fit the structural parameters for methyl formate and methyl acetate to within experimental error or better. The most recent electron diffraction work was done on methyl formate in 1980 by Craddock and Rankin,¹⁹ which gave r_a values. These have been converted to r_g values here. Recently, the structure of gaseous methyl acetate has been determined by joint analysis of electron diffraction, microwave, and infrared spectroscopy, supplemented by a valence force field calculation and constraints from geometry relaxed ab initio calculations by Pyckhout and co-workers (1985).²⁰ Structures from MM3 are in quite good agreement with this work. Table VII summarizes the structures for these two compounds from MM3 and experiment.

Methyl Formate. In 1980, Ruschin and Bauer²¹ found that the energy difference between the methyl formate *E/Z* rotamers is 3.85 ± 0.20 kcal/mol by the temperature-drift technique where the IR absorption method was applied. In 1981, Blom and Gunthard²² measured this value to be 4.75 ± 0.19 kcal/mol, and they estimated the barrier between the *Z/E* conformers as 10–15 kcal/mol from their IR work. MM3 gives these values to be 4.94 and 16.39 kcal/mol, respectively. The MM2 value was 3.73 kcal/mol for the energy difference between the *E* and *Z* conformations.²³ The rotational barrier of the methoxy methyl group is calculated to be 1.13 kcal/mol by MM3, which is consistent with the microwave value of 1.19 ± 0.04 kcal/mol by Curl.²⁴

Acetic Acid and Methyl Acetate. The internal rotational barriers of the acetate methyl group in acetic acid and methyl acetate have been reported by microwave spectroscopists. In 1957, Tabor²⁵ reported the value 483 ± 25 cal/mol, and in 1970, Krisher and Saegbarth²⁶ reported the value 480.8 ± 0.5 cal/mol for acetic acid. The potential barrier to internal rotation of the acetate methyl group has been determined as 99.56 (8) cm^{-1} (0.285

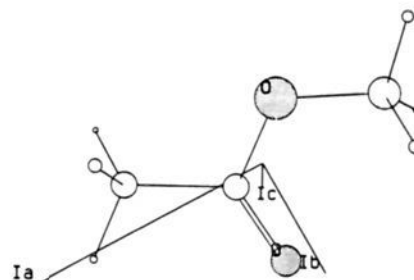
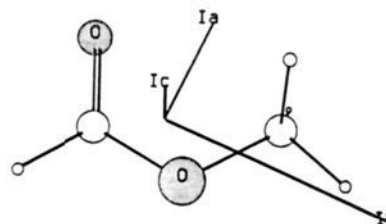


Figure 2. The MM3 structures of methyl formate (upper) and methyl acetate (lower).

kcal/mol), whereas that of the methoxy methyl group has been determined as 425 (3) cm^{-1} (1.217 kcal/mol), according to Sheridan and co-workers (in 1980).²⁷ There was no explanation of the difference between the rotational barrier of the acetate methyl group in the two compounds. MM3 calculations show that there is no significant difference in these two rotational barriers, and it calculates 0.40 kcal/mol for both acetic acid and for methyl acetate, and 1.20 kcal/mol for methoxy methyl group, which are all in good agreement with the experimental work.

The energy difference between the *E* and *Z* rotamers of methyl acetate was found to be rather high, due to the steric hindrance between the two methyl groups in (*E*)-methyl acetate. Gunthard²² estimated it to be 8.5 ± 1.0 kcal/mol from matrix IR spectra. Our MM3 calculated value is 8.71 kcal/mol, and it was 7.80 kcal/mol in MM2.²³

Ethyl Formate. This compound is calculated to have two rotational isomers with the ethyl group *cis* to the carbonyl oxygen. The *trans* isomer has the conformation with the heavy atom skeleton coplanar, while the *gauche* isomer has methyl group 77° out of the plane (C-C-O-C dihedral angle). The *trans* isomer was found by MM3 to be 0.18 kcal/mol more stable than the *gauche* isomer, with a barrier of 1.23 kcal/mol. Ethyl formate has been studied in the microwave spectrum by Riveros and Wilson;²⁸ they found that the *gauche* isomer has the methyl group 85° out of the plane. The *gauche-trans* energy difference is 0.19 ± 0.06 kcal/mol, and they estimated the *trans-gauche* barrier at 1.10 ± 0.25 kcal/mol. Our calculation is in agreement with the experimental work.

Lactones

β -Butyrolactone. Structural data for β -butyrolactone from MM3 and an estimated microwave structure from Gonzalez and co-workers (1990)²⁹ are summarized in Table VIII. The r_z values calculated by MM3 have been used here for comparison. MM3 calculations show that the bond angles for β -butyrolactone are quite different from the experimental values, and we think the reported values for the bond angles are inaccurate. Since it is a well-known experimental fact that the C-C=O angle is larger than the O-C=O angle in lactones, and for β -lactones this

(16) Derissen, J. L. *J. Mol. Struct.* **1971**, 7, 81.

(17) Stiefvater, O. L. *J. Chem. Phys.* **1975**, 62, 244.

(18) The calculations were carried out using the Gaussian 90 program with 6-31G* basis set.

(19) Craddock, S.; Rankin, D. W. H. *J. Mol. Struct.* **1980**, 69, 145.

(20) Pyckhout, W.; Van Alsenoy, C.; Geise, H. J. *J. Mol. Struct.* **1986**, 144, 265.

(21) Ruschin, S.; Bauer, S. H. *J. Phys. Chem.* **1980**, 84, 3061.

(22) Blom, C. E.; Gunthard, H. H. *Chem. Phys. Lett.* **1981**, 84, 267.

(23) Allinger, N. L.; Chang, H. S. M. *Tetrahedron* **1977**, 33, 1561.

(24) Curl, R. F., Jr. *J. Chem. Phys.* **1959**, 30, 1529.

(25) Tabor, W. J. *J. Chem. Phys.* **1957**, 27, 974.

(26) Krisher, L. C.; Saegbarth, E. *J. Chem. Phys.* **1971**, 54, 4553.

(27) Sheridan, J.; Bossert, W.; Bauder, A. *J. Mol. Spectrosc.* **1980**, 80, 1.

(28) Riveros, J. M.; Wilson, E. B., Jr. *J. Chem. Phys.* **1967**, 46, 4605.

(29) Gonzalez, E.; Lopez, J. C.; Alonso, J. L. *J. Mol. Struct.* **1990**, 223, 365.

Table VII. Structural Data from Experiment and MM3 for Methyl Formate and Methyl Acetate^a

	methyl formate ¹⁹			methyl acetate ²⁰		
	exp (r_g from r_a)	MM3 (r_g)	MM3 - exp	exp (r_g)	MM3 (r_g)	MM3 - exp
C-O (3-75)	1.343 (7)	1.3339	-0.009	1.360 (7)	1.3584	-0.002
C=O (3-78)	1.208 (5)	1.2131	0.005	1.209 (6)	1.2147	0.006
O-C (75-1)	1.447 (5)	1.4401	-0.007	1.442 (7)	1.4399	-0.002
C-C (1-3)				1.496 (7)	1.4919	-0.004
H-C (5-3)	1.103 ^b	1.1061	0.003			
O=C-O (78-3-75)	126.8 (16)	125.50	-1.3	123.0	123.13	0.1
H-C-O (5-3-75)	109.3	111.33	2.0			
C-C-O (1-3-75)				111.4	111.52	0.1
C-O-C (3-75-1)	114.3 (16)	115.71	1.4	116.4	115.80	-0.6
C-C=O (1-3-78)				125.6	125.35	-0.3
	exp ²⁰	MM3	error (%)	exp	MM3	error (%)
I_x^c	4.1990	4.2106	0.28	8.1901	8.2313	0.50
I_y	12.1367	12.2924	1.28	20.1236	20.4254	1.50
I_z	15.8208	15.9539	0.84	27.2778	27.5668	1.06

^aUnits: Å for bond length, deg for bond angle. ^bAssumed value. ^cUnits in 10^{-39} g cm⁻².

Table VIII. Structural Data from Experiments and MM3 for β -Butyrolactone

	exp ²⁹	MM3 (r_z)	MM3 - exp
O-C (75-58)	1.430	1.428	-0.002
O-C (75-56)	1.430	1.430	0.000
C-C (58-56)	1.526	1.521	-0.005
C=O (58-78)	1.169	1.162	-0.007
C-C (1-56)	1.526	1.527	0.001
C-O-C (56-75-58)	92.4	92.22	-0.2
O=C-O (78-58-75)	133.8	128.53	-5.3
O-C-C (75-58-56)	91.0	92.03	0.9
C-C=O (56-58-78)	133.8	139.44	5.6
C-C-C (56-56-58)	84.3	84.57	0.3

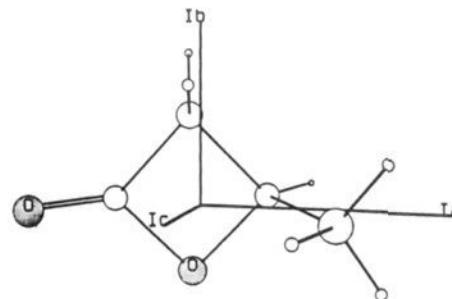
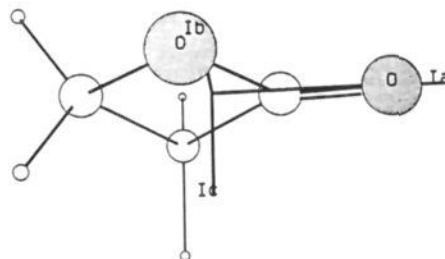
^aUnits: Å for bond length, deg for bond angle.

difference is as high as 12° ,^{30,31} it is not reasonable that the C-C=O angle is so similar to the O=C-O angle in β -butyrolactone. The I_a axis of the molecule lies approximately along the C=O bond (see the MM3 structure of β -butyrolactone). The moment of inertia is therefore insensitive to the position of oxygen atom (type 78), which makes the microwave values for these two angles particularly inaccurate. Note that MM3 fits the moments of inertia very well. The angles discussed above were also calculated at the 4-31G level by earlier workers,²⁹ and the MM3 values are in much better agreement with these ab initio values than with the reported microwave values.

Structural Characteristics of the Carboxylic Ester Group. In MM3 calculations, the carbonyl group in lactones tends to show a C-C=O angle that is larger than the O=C-O angle, the difference increasing in magnitude as the ring size decreases. This is consistent with the X-ray results,^{30,31} but the amount of this difference is not quantitatively like those in X-ray results.

The MM3 difference between the C-C=O and O=C-O angles in the chair form of valerolactone is smaller than in boat form, which is not surprising because the chair form of valerolactone is a less strained system than the boat form. The structural characteristics of the carbonyl ester group are summarized in Table IX. We were not able to fit the difference between the O=C-O and C-C=O angles any better, because further improvements here lead to a worsening of the relative energies of δ -valerolactone conformations.

Moments of Inertia and Dipole Moments. The correction of a moment of inertia from an r_g (MM3) to an r_s (microwave) basis will generally cause the value to be reduced by an amount between 0 and 1%.³² Accordingly, if the MM3 calculated moments of inertia are higher than the experimental ones by amounts in that range, we regard the agreement with experiment as acceptable. The MM3 program can also be used to interconvert r_z , r_g , r_a , and

**Figure 3.** The MM3 structures of β -propiolactone (upper) and β -butyrolactone (lower).

r_g and in some of the tables the r_z values directly from the program are given.

The moments of inertia and dipole moments of carboxylic acids and esters are reproduced pretty well by MM3, except for formic acid, which is a special case. The data are given in Tables X-XI.

In 1954, Trambarulo and Moser³³ determined the I_b and I_c values from a microwave study on formic acid, and I_a from the difference between I_b and I_c by taking formic acid as a planar conformer. The dipole moment of formic acid has been reported by different researchers,^{34,35} and the values vary a lot, 1.35 ± 0.02 D, 1.7 D, respectively (all are gas-phase values; see later). The moments of inertia of acetic acid were reported by Tabor¹³ in 1957, and remeasured by Krisher and Saegbarth³⁶ who determined the molecular parameters more accurately; they reported the dipole moment for acetic acid at the same time in 1970. In 1981, Van Eijck and co-workers reexamined the internal rotational splitting in the microwave spectrum of acetic acid, using both the principal axis method (PAM) and the internal axis method (IAM), and

(33) Trambarulo, R.; Moser, P. M. *J. Chem. Phys.* **1954**, *22*, 1622.

(34) Erlandsson, G.; Selen, H. *Ark. Fys.* **1958**, *14*, 61.

(35) Townes, C. H.; Schawlow, A. L. *Microwave Spectroscopy*; McGraw-Hill: New York, 1955.

(36) Krisher, L. C.; Saegbarth, E. *J. Chem. Phys.* **1971**, *54*, 4553.

(30) Norskov-Lauritsen, L.; Burgi, H.-B.; Hofmann, P.; Schmidt, H. R. *Helv. Chim. Acta* **1985**, *68*, 76.

(31) Schweizer, W. B.; Dunitz, J. D. *Helv. Chim. Acta* **1982**, *65*, 1547.

(32) See ref 2.

Table IX. Structural Characteristics of the Carboxylic Ester Group^a

	C—O—C	C—C=O	O—C=O	(C—C=O) - (O—C=O) MM3/X-ray ^{30,31}
β -propiolactone	92.31	139.50	128.57	11.0/12.4 (27)
γ -butyrolactone	110.26	126.91	122.96	4.0/6.9 (12)
δ -valerolactone				/4.5 (16)
half-chair form	124.74	122.11	120.45	1.7
boat form	118.42	124.20	121.49	2.7
ϵ -caprolactone	122.47	123.04	120.80	2.2/4.1 (13)
chair form				
acyclic ester				
methyl acetate	115.80	125.35	123.13	2.2/2.0 (15)

^aThe numbers in parentheses are the standard deviations.

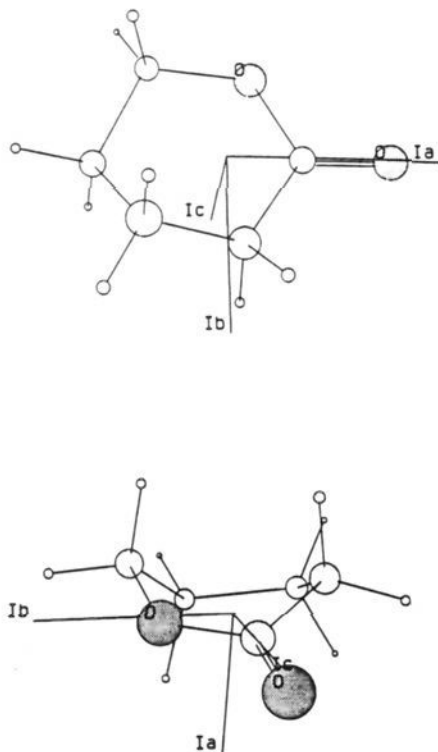


Figure 4. The MM3 structures of valerolactone: upper, chair form; lower, boat form.

they reported the rotational constants of acetic acid. Their result is in agreement with the earlier electron diffraction result.³⁶ These two sets of data (PAM and IAM) and the MM3 calculated values are summarized in Table IV. The rotational constants and dipole moment of (*Z*)-propionic acid were reported by Stiefvater.³⁷

The moments of inertia of methyl formate were reported by Curl³⁸ from an investigation of the microwave spectra of isotopic species of methyl formate in 1958, and the dipole moment was calculated from the observed Stark effect and found to be 1.77 ± 0.03 D in the same paper. The dipole moments of both the trans and gauche ethyl formate were calculated from Stark-effect measurements, yielding 1.98 ± 0.02 D and 1.81 ± 0.02 D, respectively, by Riveros and co-workers.²⁸ Zahn³⁹ and Mizushima⁴⁰ reported 1.706 D and 1.68 D for the dipole moment of methyl acetate in 1932 and 1938, respectively, and an average value of 1.9 D is used here. The rotational constants of methyl acetate have been reported by Sheridan.⁴¹ The rotational constants and the structural data for β -butyrolactone have been reported by Gonzalez et al.,²⁹ and the dipole moments by Coffey and Hershberger.⁴² Boone⁴³ has reported the dipole moment and

Table X. Moments of Inertia of Lactones (Units: 10^{-39} g cm²)

	exp	MM2	error (%)	MM3	error (%)
β-Propiolactone⁴³					
I_x	6.76	6.79	0.44	6.77	0.15
I_y	16.00	15.94	-0.38	16.13	0.82
I_z	21.69	21.54	-0.69	21.77	0.37
β-Butyrolactone²⁸					
I_x	9.0549			9.1332	0.87
I_y	31.1004			31.3233	0.72
I_z	35.2618			35.4006	0.39
γ-Butyrolactone (Envelope Form)⁴⁴					
I_x	11.53	11.54	0.09	11.56	0.26
I_y	23.41	23.44	0.13	23.55	0.60
I_z	32.75	32.71	-0.12	32.96	0.64
Valerolactone (Half-Chair Form)⁴⁵					
I_x	18.004	18.036	0.18	17.903	-0.56
I_y	32.800	33.053	0.77	33.321	1.59
I_z	47.382	47.493	0.23	47.713	0.70
Valerolactone (Boat Form)⁴⁵					
I_x	18.456	19.035	3.15	18.5444	0.48
I_y	32.329	31.970	-1.11	32.5352	0.64
I_z	44.929	44.568	-0.80	45.1899	0.58
Caprolactone (Chair Form)⁴⁶					
I_x	26.22	26.71	1.87	26.21	-0.04
I_y	43.70	43.24	-1.05	43.89	0.43
I_z	62.22	61.61	-0.98	61.90	-0.51

Table XI. Dipole Moments of Acids and Esters (Unit: Debyes)

compound	calc	exp ^a	ref
formic acid	1.73	1.7 ^b	34, 35
acetic acid	1.69	1.75	36
propionic acid	1.69	1.55 ± 0.03	37
methyl formate	1.83	1.77 ± 0.03	38
methyl acetate	1.78	1.69	39, 40
ethyl formate (trans CH ₃)	1.83	1.98 ± 0.02	28
ethyl formate (gauche CH ₃)	1.87	1.81 ± 0.02	28
propiolactone	4.28	4.17	43
β -butyrolactone	4.28	4.40 ± 0.06	42
γ -butyrolactone	4.23	4.27 ± 0.03	44
δ -valerolactone		4.22 ^c	47
boat	4.34		
half-chair	4.27		
caprolactone	4.30	4.45 ^c	47

^aThese dipole moments are determined from microwave spectra except where otherwise noted. ^bThis value is more consistent with the values of the rest of the compounds. ^cIn benzene solution.

rotational constants for β -propiolactone, but no structural details. Durig⁴⁴ has reported the rotational constants and dipole moment for γ -butyrolactone. The rotational constants of the chair and boat conformations of δ -valerolactone have been determined by experiment and by MM2.⁴⁵ The rotational constants of ϵ -ca-

(37) Stiefvater, O. L. *J. Chem. Phys.* **1975**, *62*, 233.

(38) Curl, R. F., Jr. *J. Chem. Phys.* **1959**, *30*, 1529.

(39) Zahn, C. T. *Phys. Rev.* **1932**, *730*.

(40) Mizushima, S.; Kubo, M. *Bull. Chem. Soc. Jpn.* **1938**, *13*, 174.

(41) Sheridan, J.; Bossert, W.; Bauder, A. *J. Mol. Spectrosc.* **1980**, *80*, 1.

(42) Coffey, D.; Hershberger, M. V. *J. Mol. Spectrosc.* **1976**, *59*, 28.

(43) Boone, D. W.; Britt, C. O.; Boggs, J. E. *J. Chem. Phys.* **1965**, *43*, 1190.

(44) Durig, J. R.; Li, Y. S.; Tong, C. C. *J. Mol. Struct.* **1973**, *18*, 269.

Table XII. Energies of Dimerization

	exp		MM3
formic acid	-11.69 ⁷⁰	(14.1 ± 1.5) ⁶⁹	-12.18
acetic acid		(14.2 ± 0.7) ⁶⁹	-12.14
propionic acid		(14.5 ± 1.2) ⁶⁹	-12.22

prolactone was reported by Cogley.⁴⁶

The moments of inertia are inversely proportional to the rotational constants, but the proportionality constants used by different people, including our program, are somewhat different. For those experiments in which the rotational constants are given, we converted them to the corresponding moments of inertia by using the conversion factor $83\,920.99 \text{ MHz g cm}^2 \times 10^{-39}$ (which is used in MM3) instead of using the moments of inertia given in the paper.

The moments of inertia of straight-chain acids and esters from the experiments and from MM3 were given under the discussion for the individual compounds. Table X gives similar data for the lactones. The dipole moments of some acids and esters are summarized in Table XI.

In a *Z*-conformer, the dipole moments of the C=O (3-77 or 3-78) and O-C (75-1) bonds point in opposite directions and partly cancel out. The dipole moment of a *Z*-conformer is thus smaller than that of an *E*-conformer, in which these two dipole moments point more nearly in the same direction. Also, the induced dipole moment due to the strong dipole C=O in a *Z*-conformer is in the opposite direction too, which causes the dipole moment of the *Z*-conformer to be even smaller. Conversely, the induced dipole moment causes the total dipole moment in an *E*-conformer to be even larger. Since the induced dipole moments have not been considered yet in MM3, we can only fit the dipole moments in an average way.

Formic Acid Dimer

Carboxylic acids are known to form dimers in the gas phase, and these are quite stable. The stability constants were originally measured by the temperature dependence of gas volumes.⁶⁹ More recently, the heat of dimerization of formic acid was determined by FTIR measurements.⁷⁰ Both sets of experiments appear to have been carefully done, but they show substantial discrepancies. The reason for the discrepancies is not known with certainty, but it is suspected that the FTIR method gives a better result, because the gas volume method yields not only the dimer formation, but all other associations as well. We have accordingly taken the dimerization energy of formic acid to be -11.69 kcal/mol experimentally, with a probable error of about 0.4 kcal/mol (which we conservatively estimate by allowing for undetected systematic errors). The value from gas volume measurements is 14.1 ± 1.5 kcal/mol, which seems to be constant to within experimental error over a range of carboxylic acids. The MM3 calculations give the value for formic acid as 12.18 kcal/mol, and that for acetic acid as 12.14 kcal/mol. Dimerization energies of carboxylic acids are summarized in Table XII.

The earlier determined hydrogen bonding potential for MM3 had the general characteristics of a van der Waals potential. After further study, we concluded that MM3 can better represent hydrogen bonds if a directional character is used in this potential. Accordingly, the hydrogen bond potential used in MM3 from here on will be as follows:

$$E_{\text{HB}} = [\epsilon(k) \times 10^5 \exp(-12.00)/(RV/R) - 2.25(P)^6] (1 - \cos \omega)$$

The only things about dimer formation and hydrogen bonding that are not adequately accounted for are the spectral shifts that occur upon hydrogen bonding. There is some charge transfer from the electron donor into the σ^* orbital of the X-H bond upon

Table XIII. Structure of the Formic Acid Dimer

	exp (ED) ⁷¹		MM3
C=O	1.220		1.210
C-O	1.323		1.336
O-H	1.036		0.983
O...O	2.268		2.253
O-H...O	2.703		2.730
O=C-O	126.2		124.38
H-C=O	115.4		123.76
C-O-H	108.5		108.21
O...H...O	180 (assum)		175.9
	172.7 (ab initio) ⁷²		

H-bond formation, which causes the force constant and the stretching frequency of the X-H bond to be reduced. The change in the potential surface brought about by the hydrogen bonding also causes the frequency of this vibration to be reduced. We believe the latter is properly accounted for, but the former is not currently taken into account in MM3. Therefore, in places where the shifts are relatively small (alcohols), the vibrational frequency of the hydrogen bonded hydrogen is reasonably calculated, although in cases where the shift is large, such as in the present case, there is a calculated shift, but it is much smaller than that observed experimentally.

With the directional hydrogen bonding potential, MM3 gives a reasonable account of the energy (Table XII) and structure (Table XIII) of the formic acid dimer.

Vibrational Frequencies

The vibrational frequencies for a group of alkanes were calculated with MM3 using the method of Wilson, Decius, and Cross,⁴⁸ and the overall results were refined to a root-mean-square error of around 35 cm^{-1} when comparing with experimental data.^{49,50} If the vibrational frequencies could be calculated for acids and esters with approximately that error, they would be regarded as acceptable. Calculations on several carboxylic acids and esters show that they are satisfactory.

In this study, the C=O bond length was found to be slightly but noticeably different from that in an aldehyde or ketone. The reasons for this difference are two: (a) the conjugation effect in the O=C-O group makes the C=O bond length longer, and the C=O bond force parameter weaker; (b) the electronegativity effect of the alkoxy oxygen makes the C=O bond length shorter, and the bond stronger.

These two effects partly cancel, and together they make the C=O bond longer, and the C=O bond force parameter weaker. We have therefore made the natural bond length and bond stretching parameters for the C=O bond in acids and esters distinguishable from those in a ketone or aldehyde.

For formic acid and formates, because of the electronegativity effect of the alkoxy oxygen atom which is attached to the carbonyl carbon, the H-C bond (where the C is carbonyl carbon) also becomes shorter and stronger than that in an aldehyde, with a stretching frequency more than 100 cm^{-1} higher than that in an aldehyde. When a methyl group is attached to the carbonyl carbon replacing the formate hydrogen, the electronegativity of the oxygen atom on the C-C (type 1-3) bond is not as pronounced as it is with the H-C bond, perhaps because the C atom is itself more electronegative than the H atom, and it is not necessary for us to make a correction for this bond. However, the O=C-O group as a whole is found to have a much stronger electronegativity effect on the C-H bond stretching of the methyl group than does the carbonyl group itself, raising the C-H frequency about 60 cm^{-1} relative to the ketone values. Since these effects are so large, and the errors introduced are so large if they are neglected, the program checks the neighbors of a C=O bond, and uses constants as

(47) Huisgen, R. *Angew. Chem.* 1957, 69, 341.

(45) Philip, T.; Cook, R. L.; Malloy, T. B., Jr.; Allinger, N. L.; Chang, S.; Yuh, Y. H. *J. Am. Chem. Soc.* 1981, 103, 2151.

(46) Cogley, C. D. Abstracts, Ninth Austin Symposium on Molecular Structure, Austin, TX, March 1982; p 59.

(48) Wilson, E. B., Jr.; Decius, J. C.; Cross, P. C. *Molecular Vibrations*; Dover Publications: New York, 1955.

(49) See ref 2.

(50) Lii, J.-H. Dissertation submitted to the University of Georgia in 1987, as partial fulfillment requirements for the Ph.D. degree in chemistry.

Table XIV. Vibrational Spectrum of Formic Acid (cm⁻¹)

mode	exp ⁵²	MM3	MM3 - exp
		A'	
OH stretch	3570	3577 (A')	7
CH stretch	2943	2953 (A')	10
C=O stretch	1770	1782 (A')	+12
C-O stretch	1105	1144 (A')	39
CH bend	1387	1378 (A')	-9
OH bend	1229	1218 (A')	-11
OCO bend	636	648 (A')	12
		A''	
CH bend	1033	1003 (A'')	-30
OH bend	636	615 (A'')	-21
overall	rms	20	
	avg	-1	

appropriate for the C=O (ketone, ester, amide), and also for the aldehyde-type hydrogen as well as for hydrogens attached to the α carbon.

The vibrational frequencies for formic acid, acetic acid, methyl formate, methyl acetate, β -butyrolactone, and γ -butyrolactone are summarized in Tables XIV-XX, respectively; the results were used to aid in refining the values of the force parameters needed for the MM3 force field. It was noted here, and has been noted before on numerous occasions,⁷³ that when an electronegative atom (in the case of ester, either the carbonyl carbon or the alkyl oxygen) is attached to a carbon which is in turn attached to one or more hydrogens, the stretching frequencies of the hydrogens are raised quite a bit experimentally, relative to the corresponding values in hydrocarbons. It is well known that shorter bonds which are otherwise comparable are stronger, and have higher stretching frequencies than their longer counterparts.⁷³ It is also known that the presence of electronegative atoms leads to bond shortening,⁷⁴ and so a coherent picture results. Relative to the values for the C-H stretching frequencies in hydrocarbons, compounds which have an electronegative atom in them will have some of their C-H stretching frequencies raised to higher values. The quantitative relationships for this have all been worked out and will be reported elsewhere.⁵¹

Normally we do not make changes in the force field after something has once been fixed, because of the complications involved when people try to reproduce the results. Occasionally we have made an exception to this rule, and we wish to make one here. Changing the force parameter for stretching a C-H bond changes the calculated vibrational frequency, but does not change any structural or energetic quantity significantly. Hence we have decided to implement in MM3 at this time the general relationship which will increase the stretching constants for C-H bonds in the presence of electronegative atoms. In this paper we have done the calculation both ways. First we have carried out the calculation with MM3(91), in which the stretching parameters for C-H stretching are constant at the hydrocarbon value; then we have repeated the calculation with the addition of this electronegativity effect on the stretching parameters. In Tables XV-XVIII we have given two sets of frequencies, which correspond to doing the calculation both ways. As can be seen from looking at the rms numbers, the overall results are noticeably better when this effect is taken into account (from roughly 40 cm⁻¹ to 30 cm⁻¹). The individual frequencies are much better still, with frequencies such as the formate hydrogens being improved by up to 100 wavenumbers or more when this effect is included. MM3(92) and later versions of the program will contain this modification. Although this paper is concerned only with carboxylic acids and esters, this effect is general. The presence of an electronegative atom will cause the α C-H stretching frequencies to rise by an amount that may exceed 100 wavenumbers for very electronegative groups such as fluorine or nitro, down to shifts which may be only 20 wavenumbers or so for such relatively nonpolar groups as amino nitrogen. Of course, electropositive groups cause a shift to lower frequencies, for related reasons. And, of course, the effect is not

(51) Thomas, H. Unpublished.

Table XV. Vibrational Spectrum of Acetic Acid (cm⁻¹)^a

mode	exp ⁵⁶	exp ⁵³	MM3	MM3 - exp ⁵³
		A'		
OH stretch	3577	3566	3576	10
CH ₃ asym str	2997	3051	2977/3054	-74/3
CH ₃ sym str	2961	2944	2878/2925	-66/-19
C=O str	1799	1779	1784	5
CH ₃ asym deform	1401	1439	1456/1458	17/19
COH bend, CCO asym str, CH ₃ asym def	1340	1380	1415/1427	35/47
CH ₃ sym def COH bend	1279	1280	1294/1302	14/22
COH bend, CCO asym str	1192	1181	1206	27
CH ₃ rock	990	987	932/938	-55/-49
CC str, C-O str	846	847	806	-41
CO ₂ rock, CH ₃ rock	654	581	610	29
CO ₂ bend	536	536*	501/502	-36/-34
		A''		
CH ₃ asym str	3048	2996	2973/3009	-23/13
CH ₃ asym def	1445	1434	1426/1438	-8/4
CH ₃ rock, CO ₂ wag	1068	1044	954/960	-90/-84
OH out of plane bend	654	639	660	21
CO ₂ wag	582	535	530/531	-4
CH ₃ -C rot			86	
overall	rms	41/32		
	avg	-14/-2		

^a Values above (below) the slash are before (after) the electronegativity effect on the C-H bond stretching in the methyl group.

Table XVI. Vibrational Spectrum of Methyl Formate (cm⁻¹)

mode	exp ⁵⁷	MM3	MM3 - exp
		A'	
CH ₃ asym stretch	3045	2978/3028	-67/-17
CH ₃ asym str	2969	2876/2924	-93/-15
CH str	2943	2942	-1
C=O str	1754	1779	25
CH ₃ asym bend	1465	1495/1499	30/34
CH ₃ sym bend	1445	1427/1431	-18/-14
CH in-plane bend	1371	1377	6
C-O str	1207	1232/1233	25/26
CH ₃ in-pl rock	1168	1136/1138	-32/-30
H ₃ C-O str	925	924	-1
OCO bend	767	750	-17
COC bend	325	337	12
		A''	
CH ₃ asym str	3012	2974/2998	-38/-14
CH ₃ asym bend	1454	1462/1463	8/9
CH ₃ out-pl rock	1168	1110/1112	-58/-56
CH out-pl bend	1032	1027/1031	-5/-1
COC out-pl bend (tors.)		343	
CH ₃ -O tors		143	
overall	rms	37/29	
	avg	-15/-9	

limited to substitution on the α carbon. If the electronegative substituent is placed on the β carbon, the effect is in the same direction, and the magnitude is roughly half as large as it is at the α carbon.

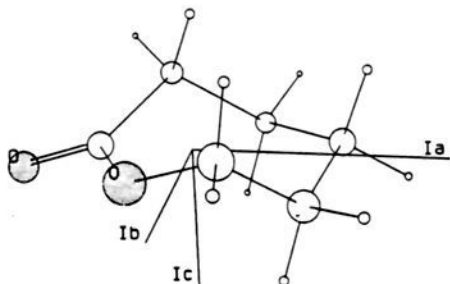
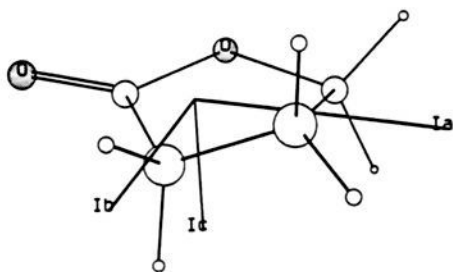
Formic Acid. Many infrared investigations of formic acid have been reported. The experimental values in Table XIV are from gas-phase infrared work by Millikan and Pitzer.⁵²

Acetic Acid. In Table XV, the standard we have used is the infrared matrix spectrum by Berney et al. in 1970,⁵³ which was assigned by Meyer et al. in 1975,⁵⁴ and revised by Hollenstein et al.⁵⁵ The value with a * was from Wilmshurst's work⁵⁶ which seems more reasonable. Hollenstein has assigned 428 cm⁻¹ to O-C-C bending, but we have calculated the O=C-O bending

(52) Millikan, R. C.; Pitzer, K. S. *J. Chem. Phys.* 1957, 27, 1305.(53) Berney, C. V.; Redington, R. L.; Lin, K. C. *J. Chem. Phys.* 1970, 53, 1713.(54) Meyer, R.; Ha, T.-K.; Frei, H.; Gunthard, H. H. *Chem. Phys.* 1975, 9, 393.(55) Hollenstein, H.; Gunthard, H. H. *J. Mol. Spectrosc.* 1980, 84, 457.(56) Wilmshurst, J. K. *J. Mol. Spectrosc.* 1957, 1, 201.

Table XVII. Vibrational Spectrum of Methyl Acetate

assign	exp ⁵⁸	MM3	MM3 - exp
A'			
O(CH ₃) as	3040	2978/3029	-62/-11
C(CH ₃) as	3040	2977/3054	-67/14
C(CH ₃) ss	2940	2878/2925	-62/-15
O(CH ₃) ss	2961	2876/2925	-85/-36
C=O s, OCC d	1771	1771	0
O(CH ₃) ab, O(CH ₃) r	1455	1509/1511	54/56
O(CH ₃) sb	1438	1450/1452	12/14
C(CH ₃) ab	1438	1417/1428	-21/-10
C(CH ₃) sb	1372	1410/1412	38/40
C(CH ₃) sb, CC s, C-O s	1249	1295/1303	46/54
O(CH ₃) r, O(CH ₃) ab	1190	1137	-53/-53
O-C s, C(CH ₃) r	1051	1070/1071	19/20
C(CH ₃) r, O-C s	982	927/932	-55/-50
C-O s, CC s, COC d	846	823/824	-23/-22
C=O ib, CC s, COC d	638	635	-3/-3
OCC d, COD d, C-O s	433	466/467	33/34
COC d, OCC d, C=O ib	302	325/326	23/24
A''			
C(CH ₃) as	3000	2973/3025	-27/25
O(CH ₃) as	3000	2974/3009	-26/9
O(CH ₃) ab	1462	1462/1466	0/4
O(CH ₃) sb	1445	1427/1439	-18/-6
O(CH ₃) r, O(CH ₃) ab	1161	1109/1111	-52/-50
O(CH ₃) r, C=O ob	1051	957/963	-94/-88
C=O ob, C(CH ₃) r	609	581/582	-28/-27
C-O t, O-C t	203	186	-17
O-C t, C-O t		144/141	
C-C t		85/86	
overall	rms	44/35	
	avg	-19/-5	

Figure 5. The MM3 structures of γ -butyrolactone (upper) and caprolactone chair form.

around this frequency. Wilmschurt has assigned 536 cm^{-1} to O=C—O bending; we think it is more reasonable to take this one as our reference. The values under the slash sign are those after the electronegativity effect corrections on the carbonyl methyl group.

Methyl Formate. The gas-phase infrared spectrum of methyl formate and assignments reported by Susi and Zell⁵⁷ have been used as our standard (Table XVI). The MM3 fit is acceptable.

(57) Susi, H.; Zell, T. *Spectrochim. Acta* **1963**, *19*, 1933.Table XVIII. Vibrational Frequencies of β -Butyrolactone

assignment	exp ^{59,a}	MM3	MM3 - exp
CH ₂ nonsymmetric stretching	3015 (R, L)	2990/2988	
CH stretching	2990	2931/2991	-59/1
CH ₃ nonsymmetric stretching	2980	2971/2970	-9/-10
CH ₃ nonsymmetric stretching	2980	2970/2969	-10/-11
CH ₂ symmetric stretching	2934 (IR, L)	2921/2923	
CH ₃ symmetric stretching	2890	2877/2877	-13/-13
C=O stretching	1861	1855/1856	-6/-5
CH ₃ nonsymmetric deformation	1455 (IR, L)	1457/1458	
CH ₂ deformation	1425	1452/1453	27/28
CH ₃ nonsymmetric deformation	1391	1454/1454	63/63
CH ₃ symmetric deformation	1357	1383/1386	26/29
C-H bending (plane)	1288	1343/1346	55/58
CH ₂ wagging	1200	1306/1310	106/110
CH ₂ twisting	1183 (IR, L)	1144/1146	
CH ₃ rocking	1130 (IR, L)	1132/1134	
ring deformation (C-O)	1111	1074/1077	-37/-34
ring deformation (C-C)	1062 (IR, L)	1012/1015	
CH ₃ rocking	1024	1003/1006	-21/-18
ring breathing	963	949/951	-14/-12
C-CH ₃ stretching	955	938/941	-17/-14
C-H bending (plane)	901 (IR, L)	913/914	
ring deformation	849	861/857	12/8
CH ₂ rocking	816	813/815	-3/-1
ring deformation	710 (IR, L)	657/658	
C=O bending (in-plane)	529	523/523	-6/-6
C=O bending (out-of-plane)	515	508/508	-7/-7
C-CH ₃ bending (to plane)	440	433/433	-7/-7
C-CH ₃ bending (to plane)	323	303/303	-20/-20
CH ₃ torsion	223	219/219	-4/-4
ring puckering	111	144/144	33/33
overall	rms	35/34	
	avg	4/8	

^a L stands for liquid phase, R for Raman.

Table XIX. Some Vibrational Frequencies of γ -Butyrolactone

assignments	exp ⁶⁰	MM3	MM3 - exp
skeletal	674 (Raman)	658	-16
in-plane bending	637 (Raman)	601	-36
carbonyl out-plane bending	536 (Raman liq phase)	532	-4
ring puckering	219 (IR liq phase)	230	11
ring puckering	160 (IR liq phase)	171	11
overall	rms 19		
	avg -7		

Methyl Acetate. Gas-phase infrared data and assignments from George and co-workers⁵⁸ have been used (Table XVII). The MM3 results are adequate.

β -Butyrolactone. The IR spectrum of β -butyrolactone in both the gas and liquid states has been recorded from 4000 cm^{-1} to 33 cm^{-1} by Durig and Morrissey.⁵⁹ Only the gas-phase values have been used as our reference on which the root-mean-square and average errors are based (Table XVIII).

γ -Butyrolactone. The infrared and Raman spectra of γ -butyrolactone have been recorded over the frequency range of 33 cm^{-1} to 1000 cm^{-1} by Durig et al.⁶⁰ The force parameters for the five-membered ring lactone have been adjusted based on these spectral data. The data are given in Table XIX.

Something More on Lactone Frequencies. It was found by experiment that the frequency of the infrared absorption maximum of the carbonyl group in esters and ketones occurs in the sequence

(58) George, W. O.; Houston, T. E.; Harris, W. C. *Spectrochim. Acta* **1974**, *30A*, 1035.(59) Durig, J. R.; Morrissey, A. C. *J. Mol. Struct.* **1968**, *2*, 377.(60) Durig, J. R.; Coulter, G. L.; Wertz, D. W. *J. Mol. Spectrosc.* **1968**, *27*, 285.

Table XX. C=O Stretching Frequencies in Lactone Compounds

lactone	C-C(=O)-O (deg)	exp ^a	MM3
propiolactone (plane)	91.93	1858	1856
γ -butyrolactone (envelope)	110.09	1790	1782
methyl acetate	111.52	1771 ^{b,58}	1771
δ -valerolactone		1760	
boat form	114.50		1766
half-chair form	117.52		1748
ϵ -caprolactone	116.15	1747	1753

^aIn CCl₄ solvent, corrected to the gas phase by +20 cm⁻¹ (see refs 62 and 63) except where otherwise noted. ^bGas phase.

four-ring > five-ring > six-ring ~ acyclic.⁶¹ This trend is well reproduced by MM3 for ketones⁶² and also for esters and lactones. This trend is mainly due to the mechanical coupling.³⁸ When the ring size gets smaller, the C-C or C-O vibrations tend to be more parallel to the C=O vibration, so that they couple more effectively. Conversely, as the ring size gets larger, these vibrations become more nearly perpendicular, and they couple less effectively. This coupling is a purely mechanical effect, which tends to make the high frequency higher and the low frequency lower. Ordinarily the C-C or C-O stretching frequencies (which are coupled with many other hydrogen bendings, etc.) are difficult to observe and interpret, but the C=O frequency, in fact, goes higher as the ring gets smaller,⁶¹ both by experiment and by MM3. The shift of frequency with ring size is often attributed^{63a} to a hybridization effect resulting in a change in force constant. This is not consistent with the MM3 calculations where, even with the same value for the stretching constant, the effect is well calculated.

Calculated and experimental values for the C=O stretching frequencies of some of lactone compounds are summarized in Table XX.

Heats of Formation

The heat of formation is a fundamental quantity of a molecule concerning the energy. Traditionally, heats of formation have been calculated by increment addition (bond energy) methods.^{1,2,68} In our molecular mechanics studies, the following equation is used:

$$\Delta H_f^\circ = BE + SE + POP + TOR + T/R$$

One uses a bond energy scheme which also includes the increments for methyl and secondary and tertiary carbons (bond enthalpy BE); the effects of strain represented by the steric energy (SE); the contributions from higher energy conformations, the POP term (POPulation of conformational levels); contributions from the vibrations involving very low torsion frequencies, TOR term; and adds these terms, together with a T/R term which accounts for the translation and rotation, and a PV term required to convert to the energy of a (nonlinear) molecule to enthalpy.

The programmed value of T/R is 2.4 kcal/mol (4RT). The TOR value is 0.0 kcal/mol for rigid system such as cyclohexane or for fused rings. In open chain molecules where torsional barriers are low, TORs may have a positive value. For the MM3 program, a torsional barrier which is less than 7.0 kcal/mol was defined as a low torsional barrier. So, if a torsional barrier is greater than 7.0 kcal/mol, the TOR term for that vibration is 0.0 kcal/mol, because it is treated as just another ordinary vibration. If a torsional barrier is less than 7.0 kcal/mol, TOR has a positive value. The POP term is 0.0 kcal/mol for a molecule which has only one conformation. If a molecule has more than one conformation, the POP value is positive. In MM3, for straight chain alkanes, when the length of chain increases by one CH₂ unit, the POP value increases by 0.35 kcal/mol; for each extra degree of freedom of the torsion motion, TOR is 0.42 kcal/mol. These values are empirically derived after a consideration of the heats of formation of a large number of hydrocarbons.

Table XXI. Input Data for the Heat of Formation Calculations in MM3

H _{sum}	E _{st}	POP	TOR	T/R	compounds
-26.29	-2.90	0.00	0.00	2.4	formic acid
-38.30	-1.46	0.00	0.00	2.4	acetic acid
-50.62	-2.19	0.00	0.00	2.4	methyl formate
-62.63	-0.88	0.00	0.00	2.4	methyl acetate
-44.85	-0.31	0.13	0.42	2.4	propionic acid
-51.59	0.78	0.48	0.84	2.4	<i>n</i> -butyric acid
-58.32	1.82	0.83	1.26	2.4	<i>n</i> -valeric acid
-60.67	2.97	0.48	0.84	2.4	isovaleric acid
-63.89	5.68	0.00	0.42	2.4	pivalic acid
-65.05	2.87	1.18	1.68	2.4	caproic acid
-71.78	3.91	1.53	2.10	2.4	heptanoic acid
-78.52	4.96	1.88	2.52	2.4	octanoic acid
-81.23	9.68	1.53	2.10	2.4	2-ethylhexanoic acid
-72.08	0.14	0.11	0.42	2.4	ethyl acetate
-82.80	1.50	0.11	0.42	2.4	isopropyl acetate
-85.54	2.22	0.81	1.26	2.4	<i>n</i> -butyl acetate
-82.65	2.37	0.83	1.26	2.4	methyl valerate
-89.38	3.42	1.18	1.68	2.4	methyl caproate
-96.11	4.46	1.53	2.10	2.4	methyl heptanoate
-78.63	1.26	0.24	0.84	2.4	ethyl propionate
-92.09	3.38	0.94	1.68	2.4	ethyl pentanoate
-98.83	4.41	1.29	2.10	2.4	<i>n</i> -propyl pentanoate
-105.56	5.45	1.64	2.52	2.4	<i>n</i> -butyl pentanoate
-88.22	6.11	0.00	0.42	2.4	methyl pivalate
-97.67	7.03	0.11	0.84	2.4	ethyl pivalate
-85.00	3.50	0.48	0.84	2.4	methyl isovalerate
-94.45	4.50	0.59	1.26	2.4	ethyl isovalerate
-85.36	5.38	0.48	0.84	2.4	methyl α -methylbutyrate
-9.80	6.35	0.59	1.26	2.4	ethyl α -methylbutyrate
-103.58	5.64	0.94	1.68	2.4	<i>sec</i> -butyl butyrate
-110.42	6.68	1.29	2.10	2.4	<i>sec</i> -butyl pentanoate
-103.58	4.71	0.94	1.68	2.4	isopropyl pentanoate
-107.14	5.89	1.29	1.68	2.4	isobutyl pentanoate
-57.40	24.77	0.00	0.00	2.4	propiolactone
-67.87	15.04	0.12	0.42	2.4	butyrolactone
-69.09	12.32	0.06	0.42	2.4	valerolactone
-75.82	16.62	0.00	0.42	2.4	caprolactone
-82.56	19.48	0.22	0.42	2.4	heptanlactone

The parameters required for the heats of formation of carboxylic acids and esters have been evaluated by a least-squares fitting of the data to the experimental values by the HT2 program. Actually, there are only three parameters (C-O in acids and esters, O-H (6-24), and H-C-O (5-3-6)) to evaluate here, as the others were previously evaluated for hydrocarbons, ketones, aldehydes, alcohols, or ethers. Experimental values with reported errors of ≥ 1.0 kcal/mol were not considered reliable and were weighted zero. The input data for the heat of formation calculation are listed in Table XXI. The preliminary calculated and experimental values^{64,65} for the heats of formation are summarized in Table XXII.

We noted that the standard deviation was 1.14 kcal/mol, which is much larger than usually observed. We concluded that this was probably because there were large systematic errors in some of the experiments that were not recognized by the experimentalists. We accordingly decided to give zero weight to several other compounds, as in Table XXIII.

The heats of formation of 38 carboxylic acids and esters were calculated. The calculated heats of formation of the straight chain compounds have been found to be in pretty good agreement with the experimental values, except a few discussed below, which could be because of inaccurate experimental values.

The difference in the heats of formation of homologues (due to the bond enthalpy of adding one CH₂ unit) is -6.73 (-4.59 \times 2 for C-H bonds and 2.447 for C-C bond) kcal/mol. This difference will usually be reduced to -4.99 kcal/mol because of the POP (0.35 kcal/mol) and TOR (0.42 cal/mol) values, and the

(61) Hall, H. K., Jr.; Zbinden, R. *J. Am. Chem. Soc.* **1958**, *80*, 6428.

(62) Dolphin, D.; Wick, A. *Tabulation of Infrared Spectral Data*; Wiley-Interscience: New York, 1977.

(63) Avram, M.; Mateescu, G. D. *Infrared Spectroscopy*; Wiley-Interscience: New York, 1966; p 431.

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

(65) Pedley, J. B.; Naylor, R. D.; Kirby, S. P. *Thermochemical Data of Organic Compounds*; Chapman and Hall: New York and London, 1986.

Table XXII. Preliminary Heats of Formation (kcal/mol)^a

eq	wt	H_f°		difference MM3 - exp	compound
		MM3	exp		
1	5	-90.30	-90.57 ± 0.14	0.27	formic acid
2	10	-103.43	-103.26 ± 0.12	-0.17	acetic acid
3	5	-85.32	-85.05 ± 0.19	-0.27	methyl formate
4	10	-98.59	-98.54 ± 0.38	-0.05	methyl acetate
5	8	-108.28	-108.40 ± 0.5	0.12	propionic acid
6	5	-113.16	-112.40 ± 0.6	-0.76	<i>n</i> -butyric acid
7	5	-118.08	-117.15 ± 0.45	-0.93	<i>n</i> -valeric acid
8	0	-120.05	-122.00 ± 1.48	1.95	isovaleric acid
9	0	-121.46	-117.54 ± 1.58	-3.92	pivalic acid
10	5	-122.99	-122.7 ± 0.5	-0.29	caproic acid
11	4	-127.91	-127.7 ± 0.5	-0.21	heptanoic acid
12	4	-132.83	-132.7 ± 0.4	-0.13	octanoic acid
13	5	-131.59	-133.85 ± 0.43	2.26	2-ethylhexanoic acid
14	10	-106.49	-106.34 ± 0.16	-0.15	ethyl acetate
15	10	-115.85	-115.12 ± 0.19	-0.73	isopropyl acetate
16	10	-116.33	-116.10 ± 0.20	-0.23	<i>n</i> -butyl acetate
17	5	-113.27	-112.7 ± 0.4	-0.57	methyl valerate
18	5	-118.18	-118.0 ± 0.4	-0.18	methyl caproate
19	5	-123.10	-123.5 ± 0.4	0.40	methyl heptanoate
20	8	-111.37	-111.00 ± 0.18	-0.37	ethyl propionate
21	4	-121.17	-121.2 ± 0.7	0.03	ethyl pentanoate
22	4	-126.11	-127.5 ± 0.5	1.39	<i>n</i> -propyl pentanoate
23	2	-131.03	-133.9 ± 0.5	2.87	<i>n</i> -butyl pentanoate
24	7	-116.77	-118.25 ± 0.31	1.48	methyl pivalate
25	0	-124.77	-128.1 ± 2.0	3.33	ethyl pivalate
26	0	-115.26	-119.0 ± 1.8	3.74	methyl isovalerate
27	0	-123.18	-126.0 ± 2.1	2.82	ethyl isovalerate
28	0	-113.74	-117.7 ± 1.8	3.96	methyl α -methylbutyrate
29	0	-121.68	-124.9 ± 2.1	3.22	ethyl α -methylbutyrate
30	0	-129.63	-130.3 ± 1.0	0.67	<i>sec</i> -butyl butyrate
31	4	-134.56	-137.0 ± 0.5	2.44	<i>sec</i> -butyl pentanoate
32	6	-130.56	-130.2 ± 0.8	-0.36	isopropyl pentanoate
33	3	-132.94	-135.9 ± 0.9	2.96	isobutyl pentanoate
34	5	-67.71	-67.60 ± 0.21	-0.11	propiolactone
35	5	-87.37	-87.0 ± 0.8	-0.37	butyrolactone
36	5	-91.37	-89.9 ± 0.8	-1.17	valerolactone
37	5	-93.86	-94.7 ± 0.6	0.84	caprolactone
38	4	-97.52	-98.3 ± 0.6	0.78	heptanlactone

^aStandard deviation = 1.14, based on 30 equations. Optimization and analysis ignore equations whose weight is zero.

steric energy increment which is empirically around 1 kcal/mol. But experimentally the difference is more than 6 kcal/mol from ethyl pentanoate to *n*-propyl pentanoate, and from *n*-propyl pentanoate to *n*-butyl pentanoate. The heats of formation of *n*-propyl pentanoate and *n*-butyl pentanoate were determined by Schjanberg in 1937.⁶⁶ The heats of formation of *n*-valeric acid, ethyl pentanoate, *sec*-butyl pentanoate, and isobutyl pentanoate were also reported in the same paper, and the latter two are also suspect.

For branch-chained compounds, because of the interactions between the O=C—O group and the branching group at an α or β position, the bond enthalpy of the branch may be different from that in ketones. (The MM3 program currently uses the same corrections for branching on the acid side of an acid carbonyl group as for a ketone.) So additional correction terms concerning this branching might be needed.

For α -branched compounds, namely, 2-ethylhexanoic acid, methyl α -methylbutyrate, and ethyl α -methylbutyrate, if we were to add an additional correction value of -1.8 kcal/mol for the α -position effect, and a correction value of -2.5 kcal/mol for the β -branched compounds, namely, isovaleric acid, methyl isovalerate, and ethyl isovalerate, the MM3 and experimental values would agree to within experimental error. These corrections are only needed for the chains attached to the carbonyl carbon, not to the oxygen atom. For isobutryl pentanoate, an O-iso structural feature may be needed. But since the experimental values here have such big reported errors, we do not feel that these kinds of corrections are desirable. The heats of formation of ethyl pivalate, methyl isovalerate, ethyl isovalerate, methyl α -methyl butyrate, and ethyl α -methylbutyrate were measured by the same group of people⁶⁷

at the same time, and none of the other compounds studied by MM3 were studied by them. The heat of formation for each of these compounds has a large reported experimental error (1.8–2.1 kcal/mol), and they are all experimentally systematically negative compared to the MM3 values by 2.7–3.8 kcal/mol. We therefore feel that these values also contain large systematic errors, as well as the reported large random errors, and we have accordingly weighted them zero.

It is not satisfying, and indeed it may seem unscientific, to discard 37% of the data before doing the parameter evaluation. But based on previous experience with many other classes of compounds, this approach is believed to yield the most realistic evaluation of the data. Fortunately, it will be possible to independently check this conclusion by calculating these heats of formation using ab initio methods.⁶⁸ These are, however, time consuming and expensive, and it will be some time before that work can be completed.

In order to compare the energies of different molecules, "strain energies" are used.¹ Some molecules exhibit strain caused by non-ideal geometries, and these kinds of molecules will be less stable than one would calculate by simply summing the energies of all the bonds and groups in the molecule. This difference is called "strain energy". A perusal of Table XXV shows that the

(67) Hancock, G. M.; Gilby, R. F. *J. Phys. Chem.* **1954**, *58*, 127.

(68) Allinger, N. L.; Schmitz, L. R.; Motoc, I.; Bender, C.; Labanowski, J. K. *J. Am. Chem. Soc.* **1991**, *114*, 2880.

(69) Mathews, D. M.; Sheet, R. W. *J. Chem. Soc., A* **1969**, 2203.

(70) Henderson, G. *J. Chem. Educ.*, **1987**, *64*, 88.

(71) Almenningen, A.; Bastiansen, O.; Motzfeldt, T. *Acta Chem. Scand.* **1969**, *23*, 2848.

(72) Chang, Y. T.; Yamaguchi, Y.; Miller, W. H.; Schaefer, H. F., III *J. Am. Chem. Soc.* **1987**, *109*, 7245.

Table XXIII. Calculated and Experimental Heats of Formation (kcal/mol)^a

eq	wt	H_f°		difference MM3 - exp	compound
		MM3	exp		
1	5	-90.24	-90.57 ± 0.14	0.33	formic acid
2	10	-103.22	-103.26 ± 0.12	0.04	acetic acid
3	5	-85.38	-85.05 ± 0.19	-0.33	methyl formate
4	10	-98.49	-98.54 ± 0.38	0.05	methyl acetate
5	8	-108.07	-108.40 ± 0.5	0.33	propionic acid
6	5	-112.95	-112.40 ± 0.6	-0.55	<i>n</i> -butyric acid
7	5	-117.87	-117.15 ± 0.45	-0.72	<i>n</i> -valeric acid
8	0	-119.84	-122.00 ± 1.48	2.16	isovaleric acid
9	0	-121.25	-117.54 ± 1.58	-3.17	pivalic acid
10	5	-122.78	-122.7 ± 0.5	-0.08	caproic acid
11	4	-127.70	-127.7 ± 0.5	0.00	heptanoic acid
12	4	-132.62	-132.7 ± 0.4	0.08	octanoic acid
13	0	-131.38	-133.85 ± 0.43	2.47	2-ethylhexanoic acid
14	10	-106.39	-106.34 ± 0.16	-0.05	ethyl acetate
15	10	-115.75	-115.12 ± 0.19	-0.63	isopropyl acetate
16	10	-116.23	-116.10 ± 0.20	-0.13	<i>n</i> -butyl acetate
17	5	-113.17	-112.7 ± 0.4	-0.47	methyl valerate
18	5	-118.08	-118.0 ± 0.4	-0.08	methyl caproate
19	5	-123.00	-123.5 ± 0.4	0.50	methyl heptanoate
20	8	-111.27	-111.00 ± 0.18	-0.27	ethyl propionate
21	4	-121.07	-121.2 ± 0.7	0.13	ethyl pentanoate
22	0	-126.01	-127.5 ± 0.5	1.49	<i>n</i> -propyl pentanoate
23	2	-130.93	-133.9 ± 0.5	2.97	<i>n</i> -butyl pentanoate
24	7	-116.67	-118.25 ± 0.31	1.58	methyl pivalate
25	0	-124.67	-128.1 ± 2.0	3.43	ethyl pivalate
26	0	-115.16	-119.0 ± 1.8	3.84	methyl isovalerate
27	0	-123.08	-126.0 ± 2.1	2.92	ethyl isovalerate
28	0	-113.64	-117.7 ± 1.8	4.06	methyl α -methylbutyrate
29	0	-121.58	-124.9 ± 2.1	3.32	ethyl α -methylbutyrate
30	0	-129.53	-130.3 ± 1.0	0.77	<i>sec</i> -butyl butyrate
31	0	-134.46	-137.0 ± 0.5	2.54	<i>sec</i> -butyl pentanoate
32	6	-130.46	-130.2 ± 0.8	-0.26	isopropyl pentanoate
33	0	-132.84	-135.9 ± 0.9	3.06	isobutyl pentanoate
34	5	-67.61	-67.60 ± 0.21	-0.01	propiolactone
35	5	-87.27	-87.0 ± 0.8	-0.27	butyrolactone
36	0	-91.27	-90.2 ± 0.8	-1.07	valerolactone
37	5	-93.76	-94.7 ± 0.6	0.94	caprolactone
38	4	-97.42	-98.3 ± 0.6	0.88	heptanlactone

^aStandard deviation = 0.55, based on 24 equations. Optimization and analysis ignores equations whose weight is zero.

Table XXIV. Input Data for the Strainless Heat of Formation

H_{sum}	E_{st}	POP	TOR	T/R	compounds
-26.04	0	0.00	0.00	2.4	formic acid
-37.87	0	0.00	0.00	2.4	acetic acid
-48.91	0	0.48	0.84	2.4	<i>n</i> -butyric acid
-60.26	0	1.18	1.68	2.4	caproic acid
-80.76	0	0.81	1.26	2.4	<i>n</i> -butyl acetate
-83.43	0	1.18	1.68	2.4	methyl caproate

inherent strain energies for simple molecules are essentially zero.

The input data for the strainless heat of formation calculation and the results are summarized in Tables XXIV and XXV. The unknown parameters, and their optimized values from the data in Table XXV are shown in Table I.

Strain energies were calculated for a representative group of compounds, and these are given in Table XXVI. We divide this strain into two parts, the first of which is called the *inherent strain*, and is a result of the actual deformations, van der Waals, and electrostatic interactions in the molecule. There is also additional strain that comes about from the POP and TOR terms. When this is added to the "inherent strain", one obtains the "total strain". Of course, strain can be defined in various ways (and has been previously in the literature). We prefer this definition, because it breaks the strain down into the component pieces so that one can see where the problem actually comes from. Further, one can compare a cyclic hydrocarbon and the corresponding lactone, for example, which one cannot do by comparing heats of formation.

(73) Herschbach, D. R.; Laurie, V. W. *J. Chem. Phys.* 1961, 35, 458, and references therein.

Table XXV. Strainless Heats of Formation of Carboxylic Acids and Esters in MM3^a

eq	wt	H_f°		difference str - MM3 ^b	compounds
		strainless	MM3*		
1	5	-90.24	-90.24	0.00	formic acid
2	10	-103.23	-103.22	-0.01	acetic acid
3	5	-112.95	-112.95	0.00	<i>n</i> -butyric acid
4	5	-122.76	-122.78	0.02	caproic acid
5	10	-116.22	-116.23	0.01	<i>n</i> -butyl acetate
6	5	-118.10	-118.08	-0.02	methyl caproate

^aThe standard deviation of 0.014 is based on six equations. ^bMM3 value from Table XXIII.

Table XXVI. Heats of Formation and Strain Energies of Some Selected Acids and Esters

compound	H_f°	inherent strain	POP	Tor	total strain energy
formic acid	-90.24	0.00	0.00	0.00	0.00
acetic acid	-103.22	0.01	0.00	0.00	0.01
butyric acid	-112.95	0.00	0.48	0.84	1.32
valeric acid	-117.87	-0.01	0.83	1.26	2.08
isovaleric acid	-119.85	-0.10	0.48	0.84	1.22
pivalic acid	-121.25	1.09	0.00	0.42	1.51
<i>n</i> -butyl acetate	-116.23	0.00	0.81	1.26	2.07
methyl caproate	-118.08	0.03	1.18	1.68	2.89
propiolactone	-67.61	20.41	0.00	0.00	20.41
butyrolactone	-87.26	8.16	0.12	0.42	8.70
valerolactone	-91.27	9.88	0.06	0.42	10.36
caprolactone	-93.75	13.13	0.00	0.42	13.55
heptanlactone	-97.41	14.93	0.22	0.42	15.57

The lactones (Table XXVI) are quite strained. Considering the large energy difference between the *cis* and *trans* conformations of an ordinary ester, it is easy to understand why. Propiolactone has a strain energy of over 20 kcal/mol, and α -lactones are commonly seen only as reactive intermediates, rather than isolable species. Butyrolactone has a strain energy calculated to be 8.70 kcal/mol, and this may seem surprisingly high, considering that γ -hydroxy acids often spontaneously ring close to form γ -lactones. The driving force for such a ring closure is, however, not the stability (enthalpy) of the lactone so much as it is the large favorable translational entropy effect which results when the water molecule is also generated. While butyrolactones often close spontaneously, valerolactones usually do not, and the extra 1.5 kcal/mol in strain of the valerolactone over the butyrolactone shows why. The seven- and eight-membered ring lactones contain relatively high strain, and such molecules are normally not obtained spontaneously, and indeed, they are obtained with con-

siderable difficulty, if at all, from most kinds of ring-closure reactions.

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Registry No. Formic acid, 64-18-6; acetic acid, 64-19-7; butyric acid, 107-92-6; valeric acid, 109-52-4; isovaleric acid, 503-74-2; pivalic acid, 75-98-9; butyl acetate, 123-86-4; methyl caproate, 106-70-7; propiolactone, 57-57-8; γ -butyrolactone, 96-48-0; δ -valerolactone, 542-28-9; ϵ -caprolactone, 502-44-3; heptanolactone, 539-87-7; methyl acetate, 79-20-9; ethyl formate, 109-94-4; β -butyrolactone, 3068-88-0; propionic acid, 79-09-4; methyl formate, 107-31-3; caproic acid, 142-62-1; heptanoic acid, 111-14-8; octanoic acid, 124-07-2; 2-ethylhexanoic acid, 149-57-5; ethyl acetate, 141-78-6; isopropyl acetate, 108-21-4; methyl valerate, 624-24-8; methyl heptanoate, 106-73-0; ethyl propionate, 105-37-3; ethyl pentanoate, 539-82-2; propyl pentanoate, 141-06-0; butyl pentanoate, 591-68-4; methyl pivalate, 598-98-1; ethyl pivalate, 3938-95-2; methyl isovalerate, 556-24-1; ethyl isovalerate, 108-64-5; methyl α -methylbutyrate, 868-57-5; ethyl α -methylbutyrate, 7452-79-1; *sec*-butyl butyrate, 819-97-6; *sec*-butyl pentanoate, 23361-94-6; isopropyl pentanoate, 18362-97-5; isobutyl pentanoate, 10588-10-0; formic acid dimer, 14523-98-9.

(74) Allinger, N. L.; Imam, M. R.; Frierson, M. R.; Yuh, Y. H.; Schaefer, L. The Effect of Electronegativity on Bond Lengths in Molecular Mechanics Calculations. In *Mathematics and Computational Concepts in Chemistry*; Trinajstić, N., Ed.; E. Horwood: London, 1986; p 8.

Vinylidene and the Hammond Postulate

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Abstract: The potential energy barrier for the isomerization of vinylidene, :C=CH_2 , to acetylene, $\text{HC}\equiv\text{CH}$, has been calculated by the quadratic configuration interaction method using a $6s6p3d2f,4s2p1d$ basis of atomic pair natural orbitals with extrapolation to the complete basis set limit (CBS-QC1/[...3d2f] APNO model). The calculated barrier ($\Delta E_c^\ddagger = 2.2 \pm 0.5$ kcal/mol) and energy change from vinylidene to acetylene ($\Delta E_0 = -43.9 \pm 0.5$ kcal/mol) are in excellent agreement with recent experimental values ($\Delta E_c^\ddagger = 2$ kcal/mol, and $\Delta E_0 = -44.1 \pm 0.7$ kcal/mol). In spite of the small barrier height for this strongly exothermic reaction, the transition state is located halfway between the reactant and product in apparent violation of the Hammond postulate. The potential energy surface for the isomerization can best be understood by considering two distinct processes. The location of the transition state is determined by the hydrogen migration, which has a significant barrier, whereas the exothermicity results from the conversion of the lone pair of vinylidene to a π bond in acetylene. Each of these processes individually satisfies the Hammond postulate.

I. Introduction

Over the years, there has been considerable interest in the chemistry of vinylidene, :C=CH_2 , the simplest unsaturated carbene.^{1,2} Theoretical studies have focused on the question of whether vinylidene actually exists as a stable species,³⁻¹⁵ while numerous experimental studies have provided evidence for the participation of vinylidene as an intermediate in chemical reactions.¹⁶⁻¹⁹ Lineberger and co-workers have recently observed vinylidene spectroscopically^{20,21} and thus provided the definitive answer to the question of the existence of vinylidene. Nevertheless, there are several aspects to this problem that warrant further investigation.

Although the formation of acetylene, $\text{HC}\equiv\text{CH}$, from vinylidene is strongly exothermic, the calculated geometry for the transition state is roughly halfway between the two,¹⁵ in apparent violation of the Hammond postulate,²² as first noted by Dykstra and Schaefer.³ The geometry of this transition state shows very little variation with the level of theory used.¹⁵ Such a well-defined transition state halfway between reactant and product is typical

of reactions with large activation energies. However, it seems peculiar in the present case, since the barrier is very small and

- (1) Stang, P. J. *Acc. Chem. Res.* **1978**, *11*, 107.
- (2) Stang, P. J. *Chem. Rev.* **1978**, *78*, 383.
- (3) Dykstra, C. E.; Schaefer, H. F. *J. Am. Chem. Soc.* **1978**, *100*, 1378.
- (4) Pople, J. A.; Krishnan, R.; Schlegel, H. B.; Binkley, J. S. *Int. J. Quantum Chem.* **1978**, *14*, 545.
- (5) Harding, L. B. *J. Am. Chem. Soc.* **1981**, *103*, 7469.
- (6) Osamura, Y.; Schaefer, H. F.; Gray, S. K.; Miller, W. H. *J. Am. Chem. Soc.* **1981**, *103*, 1904.
- (7) Krishnan, R.; Frisch, M. J.; Pople, J. A.; Schleyer, P. R. *Chem. Phys. Lett.* **1981**, *79*, 408.
- (8) Chandrasekhar, J.; Kahn, R. A.; Schleyer, P. R. *Chem. Phys. Lett.* **1982**, *85*, 493.
- (9) Pople, J. A. *Pure Appl. Chem.* **1983**, *55*, 343.
- (10) Pople, J. A.; Raghavachari, K.; Frisch, M. J.; Binkley, J. S.; Schleyer, P. R. *J. Am. Chem. Soc.* **1983**, *105*, 6389.
- (11) Frenking, G. *Chem. Phys. Lett.* **1983**, *100*, 484.
- (12) Carrington, T., Jr.; Hubbard, L. M.; Schaefer, H. F.; Miller, W. H. *J. Chem. Phys.* **1984**, *80*, 4347.
- (13) Binkley, J. S. *J. Am. Chem. Soc.* **1984**, *106*, 603.
- (14) Sakai, S.; Morokuma, K. *J. Phys. Chem.* **1987**, *91*, 3661.
- (15) Gallo, M. M.; Hamilton, T. P.; Schaefer, H. F. *J. Am. Chem. Soc.* **1990**, *112*, 8714.
- (16) Davison, P.; Frey, H. M.; Walsh, R. *Chem. Phys. Lett.* **1985**, *120*, 227.

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