

Origin of the Acidity Enhancement of Formic Acid over Methanol: Resonance versus Inductive Effects

Jennifer Holt and Joel M. Karty*

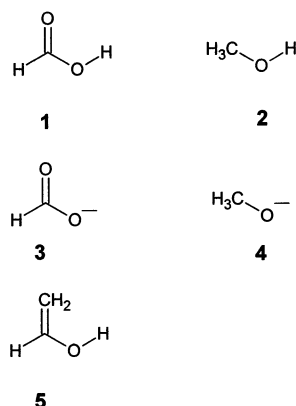
Contribution from the Department of Chemistry, Elon University, 2625 Campus Box, Elon, North Carolina 27244

Received June 6, 2002; Revised Manuscript Received December 10, 2002; E-mail: jkarty@elon.edu

Abstract: Density functional theory calculations were employed to study the relative contribution of resonance versus inductive effects toward the 37 kcal/mol enhanced gas-phase acidity ($\Delta H^\circ_{\text{acid}}$) of formic acid (**1**) over methanol (**2**). The gas-phase acidities of formic acid, methanol, vinyl alcohol (**5**), and their vinylogues (**6**, **8**, and **9**) were calculated at the B3LYP/6-31+G* level of theory. Additionally, acidities were calculated for the formic acid and vinyl alcohol vinylogues in which the formyl group and the vinyl group, respectively, were perpendicular to the rest of the conjugated system. Comparisons among these calculated acidities suggest that inductive effects are the predominant effects responsible for the enhanced acidity of formic acid over methanol, accounting for between roughly 62% and 65% of the total enhanced acidity; the remaining 38% to 35% of the acidity enhancement appears to be due to resonance effects. Further comparisons suggest that resonance effects are between roughly 58% and 65% of the 26 kcal/mol calculated acidity enhancement of vinyl alcohol over methanol, and the remaining 42% to 35% are due to inductive effects.

Introduction

Considerable disagreement surrounds the origin of the 37 kcal/mol enhanced gas-phase acidity¹ ($\Delta H^\circ_{\text{acid}}$) of formic acid (**1**) over methanol (**2**). Nearly five decades ago, Wheland² proposed two possible contributions to the enhanced acidity: (1) resonance stabilization in the formate anion (**3**) (Figure 1a) not present in the methoxide ion (**4**) and (2) inductive stabilization of the negative charge on the oxygen in the formate anion by the neighboring carbonyl group (Figure 1b). The conven-



tional³⁻⁵ explanation has been resonance stabilization in the formate anion. However, Siggel and Thomas⁶ provided evidence

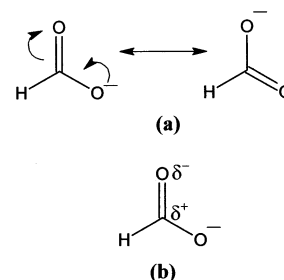


Figure 1. (a) Resonance structures of the formate anion. The negative charge is delocalized onto both oxygen atoms. (b) Inductive stabilization in the formate anion. The partial positive charge on the carbonyl carbon stabilizes the full negative charge on the oxygen atom.

that first challenged this traditional view, suggesting that the enhanced acidity is instead due to a higher potential energy at the proton in formic acid than that in methanol, as a result of the interaction between the positively charged acidic proton and the polarized carbonyl bond in formic acid (Figure 2). The ideas put forth by Siggel and Thomas have been met with both opposition⁷⁻¹⁵ and support.^{3,16-23} The issues central to this

(1) Bartmess, J. E. In *NIST Chemistry WebBook, NIST Standard Reference Database 69*; Mallard, W. G., Linstrom, P. J., Eds.; National Institute of Standards and Technology: Gaithersburg, MD, 1998.
 (2) Wheland, G. W. *Resonance in Organic Chemistry*; Wiley: New York, 1955.
 (3) Thomas, T. D. *J. Chem. Soc., Perkin Trans. 2* **1994**, 9, 1945-1948.
 (4) March, J. *Advanced Organic Chemistry*, 3rd ed.; Wiley: New York, 1985.

(5) Lowry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*, 3rd ed.; HarperCollins: New York, 1987.
 (6) Siggel, M. R. F.; Thomas, T. D. *J. Am. Chem. Soc.* **1986**, *108*, 4360-4363.
 (7) Exner, O. *J. Org. Chem.* **1988**, *53*, 1810-1812.
 (8) Exner, O.; Carsky, P. *J. Am. Chem. Soc.* **2001**, *123*, 9564-9570.
 (9) Dewar, M. J. S.; Krull, K. L. *J. Chem. Soc., Chem. Commun.* **1990**, 4, 333-334.
 (10) Godfrey, M. *Tetrahedron Lett.* **1990**, *31*, 5181-5184.
 (11) Taft, R. W.; Koppel, I. A.; Topsom, R. D.; Anvia, F. *J. Am. Chem. Soc.* **1990**, *112*, 2047-2052.
 (12) Perrin, C. L. *J. Am. Chem. Soc.* **1991**, *113*, 2865-2868.
 (13) Bordwell, F. G.; Satish, A. V. *J. Am. Chem. Soc.* **1994**, *116*, 8885-8889.
 (14) Hiberty, P. C.; Byrman, C. P. *J. Am. Chem. Soc.* **1995**, *117*, 9875-9880.
 (15) Neto, J. D. M.; Nascimento, M. A. C. *J. Phys. Chem.* **1996**, *100*, 15105-15110.

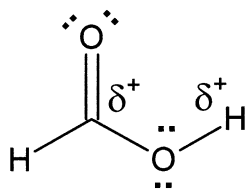
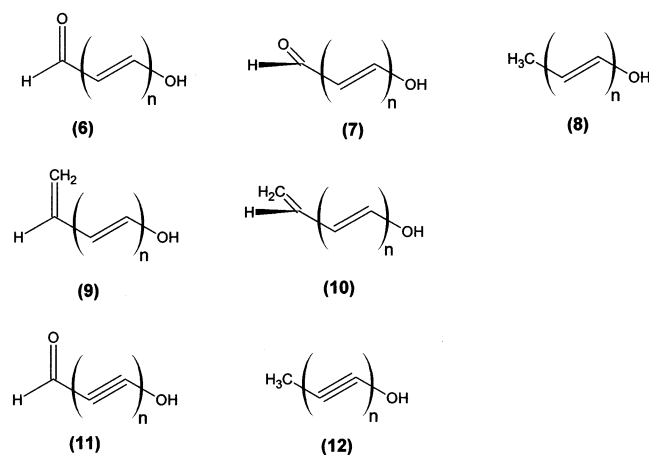


Figure 2. Illustration of the high potential energy at the acidic proton in formic acid as a result of the electrostatic repulsion between the carbonyl carbon and the acidic proton.

ongoing controversy are thoroughly outlined by Rablen,²³ as well as by Burk et al.,²⁴ and can be summarized in two questions: (1) Is the enhanced acidity a result of extra stabilization in the formate anion, relative to the methoxide anion, or is it the result of a higher potential energy at the acidic proton in formic acid than at the acidic proton in methanol, and (2) is the enhanced acidity a result of resonance or inductive effects?

Our work addresses the second of these two questions, by making use of the calculated acidities of formic acid and methanol, along with their respective vinylogues ((form_{C=C})_n, **6**, and (meth_{C=C})_n, **8**) up to $n = 3$. Acidities are also calculated



for the same vinylogues, in which the HC=O moiety is rotated 90° to the remainder of the conjugated system ((form_{C=C,⊥})_n, **7**), thereby removing the resonance effects of the formyl group toward the vinylogue acidity (Figure 3).⁵ Consequently, the difference in acidities between corresponding (same n) molecules of (form_{C=C})_n and (form_{C=C,⊥})_n, that is, $\Delta_n(\text{form}_{C=C}; \text{form}_{C=C,\perp})$, represents the resonance contribution, $\Delta H_{\text{res}}[(\text{form}_{C=C})_n]$, by the HC=O group toward the acidity of that vinylogue, (form_{C=C})_n. On the other hand, the inductive effect of the HC=O group on the acidity of the vinylogue, $\Delta H_{\text{ind}}[(\text{form}_{C=C})_n]$, should be about the same in corresponding molecules of (form_{C=C})_n and (form_{C=C,⊥})_n, because the distance between the HC=O and the OH (or O⁻) groups is essentially unchanged upon rotation of the HC=O group.

(16) Siggel, M. R. F.; Streitwieser, A. R., Jr.; Thomas, T. D. *J. Am. Chem. Soc.* **1988**, *110*, 8022–8028.

(17) Thomas, T. D.; Carroll, T. X.; Siggel, M. R. F. *J. Org. Chem.* **1988**, *53*, 1812–1815.

(18) Thomas, T. D.; Siggel, M. R. F.; Streitwieser, A. *THEOCHEM* **1988**, *165*, 309–318.

(19) Wiberg, K. B.; Laidig, K. E. *J. Am. Chem. Soc.* **1988**, *110*, 1872–1874.

(20) Wiberg, K. B. *J. Am. Chem. Soc.* **1990**, *112*, 3379–3385.

(21) Ji, D.; Thomas, T. D. *J. Phys. Chem.* **1994**, *98*, 4301–4303.

(22) Wiberg, K. B.; Ochterski, J.; Streitwieser, A. *J. Am. Chem. Soc.* **1996**, *118*, 8291–8299.

(23) Rablen, P. R. *J. Am. Chem. Soc.* **2000**, *122*, 357–368.

(24) Burk, P.; von Rague Schleyer, P. *THEOCHEM* **1999**, *505*, 161–167.

Therefore, an acidity difference between corresponding molecules of (form_{C=C,⊥})_n and (meth_{C=C})_n, that is, $\Delta_n(\text{form}_{C=C,\perp}; \text{meth}_{C=C})$, should provide a measure of $\Delta H_{\text{ind}}[(\text{form}_{C=C})_n]$, given the absence of an inductive effect provided by the CH₃ group toward the acidity of (meth_{C=C})_n. The resonance contribution toward the acidity of formic acid, $\Delta H_{\text{res}}[\text{formic acid}]$ is determined by plotting $\Delta H_{\text{res}}[(\text{form}_{C=C})_n]$ against n , for $n = 1-3$, and extrapolating to $n = 0$. Similarly, the inductive contribution toward the acidity enhancement of formic acid over methanol, $\Delta H_{\text{ind}}[\text{formic acid}]$, is determined directly by plotting $\Delta H_{\text{ind}}[(\text{form}_{C=C})_n]$ against n , for $n = 1-3$, and extrapolating to $n = 0$.

Extrapolation of $\Delta H_{\text{res}}[(\text{form}_{C=C})_n]$ to $n = 0$ yields a value of $\Delta H_{\text{res}}[\text{formic acid}]$ of about 13.5 kcal/mol, suggesting that the remainder of the 39 kcal/mol calculated acidity enhancement of formic acid over methanol (i.e., about 25.5 kcal/mol) is due to the inductive contribution, $\Delta H_{\text{ind}}[\text{formic acid}]$. Extrapolation of $\Delta H_{\text{ind}}[(\text{form}_{C=C})_n]$ yields a value of $\Delta H_{\text{ind}}[\text{formic acid}]$ of about 24 kcal/mol, suggesting that the remaining 15 kcal/mol are due to resonance.

To our knowledge, ours is the first study involving such an extrapolation of the resonance contribution by a substituent toward the thermodynamics of a chemical reaction. Our method of extrapolating $\Delta H_{\text{ind}}[(\text{form}_{C=C})_n]$, however, is related to one employed by Siggel et al.¹⁶ They examined the acidity of hydroxyacetone, CH₃C(=O)CH₂OH, employing an empirical relationship derived by Charton²⁵ to take into account the effect of the intervening CH₂ group on the inductive contribution. Charton's relationship showed that, for alcohols of the form YOH, where Y is a functional group, the insertion of a CH₂ group between Y and the OH group attenuates the inductive contribution of Y on the alcohol's acidity by a factor of about 2.6 ± 0.2 . The inductive contribution of the CH₃C=O group in CH₃C(=O)CH₂OH, determined by Charton, was therefore multiplied by 2.6 to arrive at the inductive contribution of the CH₃C=O group in acetic acid. From this analysis, Siggel et al. reported that about 80% of the acidity enhancement of acetic acid over ethanol is due to inductive effects.

Although these results are in agreement with ours, the validity of the extrapolation by Siggel et al. is not obvious. The underlying assumption is that resonance between the CH₃C=O group and the OH group (and the oxyanion) in the acetic acid system does not affect the charge distribution and, therefore, does not perturb the inductive contribution by the CH₃C=O group. However, it is not clear that this should be the case. While the validity of both types of our extrapolations are likewise not obvious, they are self-consistent, which helps to substantiate our methodology.

Our work also addresses a computational study by Dewar and Krull,⁹ which disagrees with our results. Dewar and Krull employed semiempirical AM1 calculations to calculate the acidities of formic acid and vinyl alcohol (**5**), along with the acidities of their respective vinylogues ((form_{C=C})_n and (vin_{C=C})_n, **9**). It was assumed that the inductive effects provided by the vinyl group, HC=CH₂, toward the acidity of (vin_{C=C})_n was essentially zero. Therefore, if the difference in acidities between corresponding molecules of (form_{C=C})_n and (vin_{C=C})_n (i.e., $\Delta_n(\text{form}_{C=C}; \text{vin}_{C=C})$) was dependent on n , then that dependence should be a result only of the diminishing inductive

(25) Charton, M. *Prog. Phys. Org. Chem.* **1981**, *13*, 119.

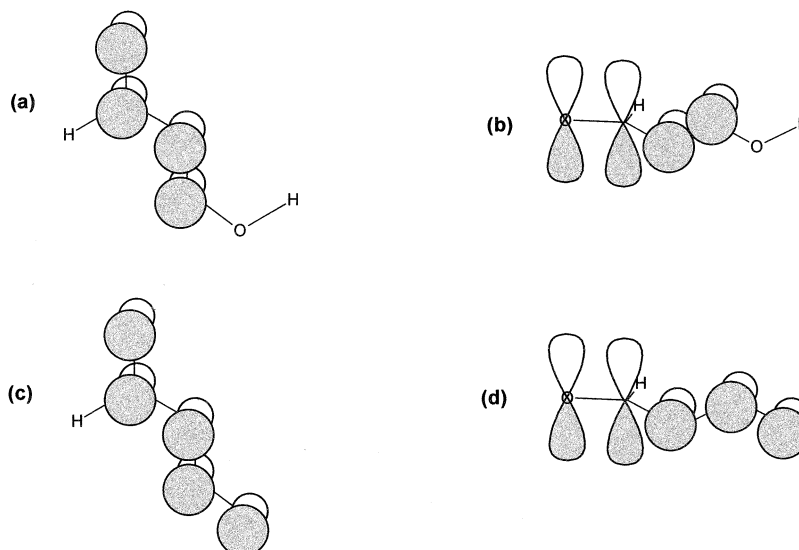


Figure 3. $n = 1$ vinylogue of formic acid with the HC=O group (a) parallel to and (b) perpendicular to the rest of the conjugated system, along with the $n = 1$ vinylogue of the formate anion with the HC=O group (c) parallel to and (d) perpendicular to the rest of the conjugated system. With the HC=O group perpendicular, the p orbitals of the carbonyl C and O do not overlap with those from the rest of the conjugated system, thereby precluding resonance effects of the HC=O group on the acidity of the vinylogue.

effects the carbonyl group has on the negative charge in the anion of $(\text{form}_{\text{C}=\text{C}})_n$. Their results showed that $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C}})$ was not significantly dependent on n and, furthermore, was about the same as the acidity enhancement of formic acid over vinyl alcohol. They therefore concluded that the enhanced acidity of formic acid over methanol was almost entirely due to resonance in the anion.

The conclusions reached by Dewar and Krull, however, appear to be invalid.²⁶ Using a method similar to that which we introduced previously for the study of the calculated enhanced acidity of formic acid over methanol, we show that about 9–11 kcal/mol of the 26 kcal/mol calculated acidity enhancement of vinyl alcohol over methanol are due to inductive effects of the vinyl group, thereby nullifying the key assumption made by Dewar and Krull. Furthermore, we show that the resonance effect of the HC=CH₂ group on the acidity of $(\text{vin}_{\text{C}=\text{C}})_n$ is significantly dependent on n , whereas the resonance effect of the HC=O group on the acidity of $(\text{form}_{\text{C}=\text{C}})_n$ is not. It therefore appears that the lack of dependence of $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C}})$ on n is a result of the compensation between the dependence of the resonance contribution on n and the dependence of the inductive contribution on n in the two different acids (see Discussion).

We revisit Dewar and Krull's model in the discussion, using a more appropriate set of comparisons: the formic acid vinylogues to the methanol vinylogues and the formic acid alkynylogues (**11** = $(\text{form}_{\text{C}=\text{C}})_n$) to the methanol alkynylogues (**12** = $(\text{meth}_{\text{C}=\text{C}})_n$). Using these comparisons, Dewar and Krull's model does indeed suggest that inductive effects account for the majority of the acidity enhancement of formic acid over methanol. These results are in agreement with our extrapolations of $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ and $\Delta H_{\text{ind}}[(\text{form}_{\text{C}=\text{C}})_n]$ to $n = 0$.

(26) Thomas (Thomas, T. D. *J. Chem. Soc., Perkin Trans. 2* **1994**, 9, 1945–1948) also points out that the results obtained by Dewar and Krull do not provide insight into the question of whether the enhanced acidity of formic acid over methanol is due to stabilization of the anion or an increased potential energy at the proton in the acid.

Computational Methods

Geometries of each acid and anion were optimized using density functional theory (DFT) calculations (Gaussian 98W) at the B3LYP/6-31+G* level of theory,²⁷ as well as semiempirical AM1 calculations. Geometries of the $n = 0$ and $n = 1$ vinylogues were optimized at the higher G2 level.²⁸ Frequency calculations were performed on each DFT and G2 optimized geometry to ensure that there were no imaginary frequencies at the stationary point, as well as to apply thermal corrections (298.15 K) to the enthalpies. The DFT and G2 acidities ($\Delta H^{\circ}_{\text{acid}}$) were computed by subtracting the thermally corrected enthalpy of the acid from the sum of the thermally corrected enthalpies of the anion and the proton. Relative AM1 acidities were computed by subtracting the bottom of the well energy of the anion from that of the acid. Input geometries for the DFT and G2 calculations were obtained via AM1 geometry optimizations, using PC Spartan Pro (Wavefunction, Inc.).

The conformation used for formic acid was the Z isomer, which has previously been shown to be the lowest energy conformation.²⁹ In each formic acid vinylogue, the OH conformation, relative to the C=O bond, was also Z, to maintain similar electrostatic interactions between the two functional groups as the distance between them is increased. In all of the vinylogues, each C=C double bond was in the E conformation; therefore, effects of conformation on the thermodynamic properties of each species should cancel when the acidity differences between the formic acid and methanol vinylogues are computed. Similarly, the conformation of vinyl alcohol was the Z isomer, and each C=C conformation in its vinylogues was the E conformation.

Results

Table 1 contains DFT and G2 calculated absolute acidities ($\Delta H^{\circ}_{\text{acid,calc}}$) and AM1 calculated relative acidities. Table 1 also contains the experimental acidities ($\Delta H^{\circ}_{\text{acid,exp}}$) of methanol and formic acid. Table 2 contains relevant DFT, G2, and AM1

(27) (a) Becke, A. D. *J. Chem. Phys.* **1993**, 98, 5648–5652. (b) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, 37, 785–789. (c) Miehlich, B.; Savin, A.; Stoll, H.; Preuss, H. *Chem. Phys. Lett.* **1989**, 157, 200–206. (d) Stephens, P. J.; Devlin, F. J.; Chabalowski, C. F.; Frisch, M. J. *J. Phys. Chem.* **1994**, 98, 11623.
 (28) Curtiss, L. A.; Raghavachari, K.; Trucks, G. W.; Pople, J. A. *J. Chem. Phys.* **1991**, 94, 7221.
 (29) Tadayoni, B. M.; Huff, J.; Rebek, J. *J. Am. Chem. Soc.* **1991**, 113, 2247.

Table 1. Calculated^{a,b,c} and Experimental Acidities^d of the Vinylogues and Alkynylogues of Formic Acid, Vinyl Alcohol, and Methanol^{e,f}

n	vinylogues												alkynylogues										
	(form _{C=C}) _n				(form _{C=C,⊥}) _n			(vin _{C=C}) _n			(vin _{C=C,⊥}) _n			(meth _{C=C}) _n									
	calcd				calcd			calcd			calcd			calcd									
DFT	G2	AM1 ^g	exptl	DFT	G2	AM1	DFT	G2	AM1 ^g	DFT	G2	AM1	DFT	G2	AM1	exptl	DFT	AM1	DFT	AM1			
0	336.8	341.9	30.2	345.3 ± 2.3						349.6	354.9	38.6				375.8	381.1	60.7	382.0 ± 1.0	336.8	30.2	375.8	60.7
1	321.5	327.4	10.0		334.1	341.5	22.4	336.7	343.2	23.1	345.5	351.5	31.9	351.9	357.1	35.5				300.0	-7.2	331.1	15.5
2	314.8		3.5		327.1		12.7	328.8		14.7	335.2		19.9	339.4		22.2				288.4	-17.9	311.5	-2.6
3	310.9		0		322.0		7.0	323.2		9.5	328.0		12.8	331.3		14.5				280.7	-23.3	299.2	-12.4

^a Thermal corrections (298.15 K) were applied to all DFT calculated acidities. ^b DFT denotes the B3LYP/6-31+G* level of theory. ^c AM1 calculated acidities are relative to that of the *n* = 3 vinylogue of formic acid. ^d All units are kcal/mol. ^e For both the vinylogues and the alkynylogues, *n* = 0 denotes the parent acid. ^f The only available experimental values (ref 1) are those of methanol and formic acid. ^g First calculated by Dewar and Krull (ref 9).

Table 2. Calculated^a Acidity Enhancements^b ($\Delta\Delta H^\circ_{\text{acid,calc}}$) of Corresponding Vinylogues and Alkynylogues^c

n	vinylogues												alkynylogues										
	$\Delta_n(\text{form}_{\text{C=C}}; \text{form}_{\text{C=C,⊥}})$			$\Delta_n(\text{form}_{\text{C=C,⊥}}; \text{meth}_{\text{C=C}})$			$\Delta_n(\text{form}_{\text{C=C}}; \text{meth}_{\text{C=C}})$			$\Delta_n(\text{vin}_{\text{C=C}}; \text{vin}_{\text{C=C,⊥}})$			$\Delta_n(\text{vin}_{\text{C=C,⊥}}; \text{meth}_{\text{C=C}})$			$\Delta_n(\text{vin}_{\text{C=C}}; \text{meth}_{\text{C=C}})$			$\Delta_n(\text{form}_{\text{C=C}}; \text{vin}_{\text{C=C}})$			$\Delta_n(\text{form}_{\text{C=C}}; \text{meth}_{\text{C=C}})$	
	DFT	G2	AM1	DFT	G2	AM1	DFT	G2	AM1	DFT	G2	AM1	DFT	G2	AM1	DFT	G2	AM1	DFT	G2	AM1	DFT	AM1
0							39.0	39.2	30.5						26.2	26.6	22.2	12.8	13.0	8.4	39.0	30.5	
1	12.6	14.1	12.4	17.8	15.6	13.2	30.4	29.7	25.5	8.8	8.3	8.8	6.4	5.6	3.6	15.2	13.9	12.5	15.2	15.8	13.1	31.1	22.7
2	12.3		9.2	12.3		9.6	24.6		18.8	6.4	5.2	4.2	2.4	10.6		7.5	14.0		11.2	23.1	15.3		
3	11.1		7.0	9.3		7.5	20.4		14.5	4.8	3.3	3.3	1.7	8.1		5.0	12.3		9.5	18.5	10.9		

^a Thermal corrections (298.15 K) were applied to all DFT calculated acidities. ^b All units are kcal/mol. ^c $\Delta_n(x; y) = \Delta H^\circ_{\text{acid,calc}}(y) - \Delta H^\circ_{\text{acid,calc}}(x)$.

Table 3. Natural Population Analysis (B3LYP/6-31+G*) of Atomic Charges

n	O on HC=O in (form _{C=C}) _n	C in HC=CH ₂ in (vin _{C=C}) _n
0	-0.807	-0.841
1	-0.726	-0.665
2	-0.693	-0.611
3	-0.674	-0.577

differences in acidities ($\Delta\Delta H^\circ_{\text{acid,calc}}$) between corresponding vinylogues. Differences in acidities between corresponding alkynylogues of formic acid and methanol are also presented in Table 2. Figure 6 plots the difference in the DFT calculated acidities between (meth_{C=C})_n and (form_{C=C})_n as a function of *n*. Figure 7 plots the difference in the DFT calculated acidities between (meth_{C=C})_n and (form_{C=C})_n as a function of *n*. Table 3 contains the natural charges on the O atom in the HC=O group of (form_{C=C})_n and the terminal C atom of the HC=CH₂ group of (vin_{C=C})_n.

Discussion

The DFT and G2 calculated absolute acidities of formic acid and methanol are in fair agreement with experimental acidities³⁰ (Table 1). The difference between the experimental and the DFT calculated acidities for methanol is 6.2 kcal/mol, and that for formic acid is 8.5 kcal/mol; with the G2 calculations, those differences are 0.9 and 3.4 kcal/mol, respectively. The DFT calculated difference in acidities between formic acid and methanol is 39.0 kcal/mol, and the G2 calculated difference in acidities is 39.2 kcal/mol; both are in excellent agreement with the difference in experimental values of 37 kcal/mol.¹ The difference between experimental and AM1 values is 30.6 kcal/mol.

Experimental acidities of vinyl alcohol and all of the vinylogues and alkynylogues are not known; a comparison

between experimental and calculated acidities for these compounds can therefore not be made. However, it is the calculated differences in acidities that are central to this work. We believe that the DFT calculated differences in acidities between corresponding (same value of *n*) vinylogues of formic acid, vinyl alcohol, and methanol are reliable for two reasons: (1) The DFT calculated acidity difference between the formic acid and methanol parent acids is in excellent agreement with the difference in experimental acidities, and (2) errors that occur in the calculated absolute acidities are expected to largely cancel when the differences in acidities between corresponding vinylogues are computed. This is supported by the excellent agreement between the DFT and the higher level G2 calculations (Table 2). Cancellation of these errors is also supported by the comparison between the DFT and AM1 calculations (Tables 1 and 2); whereas the agreement in absolute acidities is poor, the agreement in relative acidities is quite good.

Given the general agreement between our AM1 and DFT calculations, we focus the remainder of the Discussion only on the higher level DFT calculations.

Formic Acid versus Methanol. From comparisons of the calculated and experimental acidities of only the parent acids, formic acid and methanol, the origin of the enhanced acidity of formic acid over methanol is not obvious. There are potentially at least four independent contributions: (1) extra resonance stabilization in the formate anion (Figure 1a),^{2,4,5,31} (2) extra inductive stabilization in the formate anion (Figure 1b),^{2,31} (3) higher potential energy at the acidic proton in formic acid than that in methanol, resulting from inductive effects, (Figure 2)^{6,16,31} and (4) higher potential energy at the acidic proton in formic acid than that in methanol, resulting from resonance (Figure 4).³ Comparisons among the acidities of (form_{C=C})_n, (form_{C=C,⊥})_n, and (meth_{C=C})_n (Tables 1 and 2) provide insight into the sum of the first and fourth of these contributions, relative

(30) Merrill and Kass (Merrill, G. N.; Kass, S. R. *J. Phys. Chem.* **1996**, *100*, 17465–17471) were the first to show agreement between the DFT calculated (BLYP) and the experimental values of acidity for both methanol and formic acid. Our B3LYP values are in excellent agreement with their BLYP values.

(31) Solomons, G.; Fryhle, C. *Organic Chemistry*; 7th ed.; John Wiley & Sons: New York, 2000.

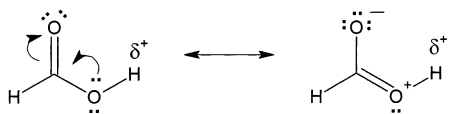


Figure 4. Resonance structures of formic acid. The positive charge on the oxygen in the structure on the right contributes to an increase in potential energy at the acidic proton via electrostatic repulsion.

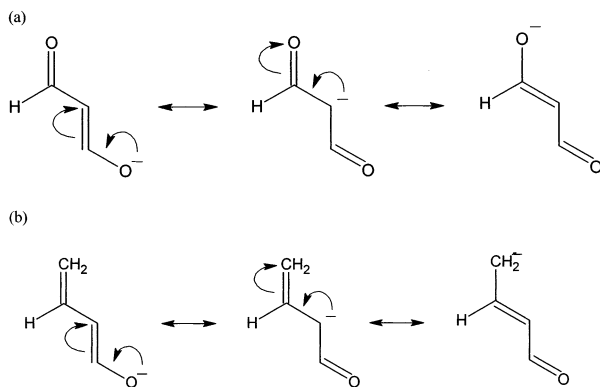


Figure 5. (a) Resonance structures of the $n = 1$ vinyllogue of the formate anion. (b) Resonance structures of the $n = 1$ vinyllogue of the conjugate base of vinyl alcohol. For each parent compound, each additional vinyl unit introduces an additional resonance structure.

to the second and the third—that is, resonance versus inductive effects.

It appears that $(\text{form}_{\text{C}=\text{C}})_n$, $(\text{form}_{\text{C}=\text{C},\perp})_n$, and $(\text{meth}_{\text{C}=\text{C}})_n$ are all more acidic with increasing n (Table 1). There are at least two reasons for this. First, with increasing n , the species is more massive and, therefore, more polarizable. This allows for greater internal solvation of the resulting negative charge after deprotonation, which provides additional stabilization in the anion.³² Second, each added unsaturated unit provides additional resonance stabilization of the resulting anion (Figure 5a).^{5,9}

$\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ appears to be relatively constant with n . It can therefore be said that $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ is relatively constant with n . $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ represents the difference in acidities between the formic acid vinyllogues, with the $\text{HC}=\text{O}$ group parallel and perpendicular to the remainder of the conjugated system. With the $\text{HC}=\text{O}$ group parallel to the conjugated system, the unhybridized p orbitals of the carbonyl C and O can participate in resonance with the hydroxyl moiety of the neutral acid and the oxyanion of its conjugate base. With the $\text{HC}=\text{O}$ group perpendicular, those orbitals are precluded from participating in such resonance (Figure 3).⁵

Extrapolation of $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ to $n = 0$ yields $\Delta H_{\text{res}}[\text{formic acid}]$. Table 2 shows that as n decreases from 3 to 1, $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ increases monotonically, albeit slowly, from 11.1 kcal/mol to 12.6 kcal/mol. A simple linear extrapolation to $n = 0$ yields 13.5 ± 0.5 kcal/mol, suggesting that about 13.5 kcal/mol (about 35%) of the 39.0 kcal/mol acidity enhancement of formic acid over methanol are due to resonance effects and the remaining 25.5 kcal/mol (about 65%) are due to inductive effects.

$\Delta H_{\text{ind}}[\text{formic acid}]$ can also be directly extrapolated from the acidity enhancements listed in Table 2. In $(\text{form}_{\text{C}=\text{C},\perp})_n$, resonance effects of the $\text{HC}=\text{O}$ group on acidity have been removed, but the inductive effects should remain essentially unchanged from those in $(\text{form}_{\text{C}=\text{C}})_n$. In $(\text{meth}_{\text{C}=\text{C}})_n$, however,

no such inductive effects should be present, as there are no significantly electronegative atoms in the CH_3 group. Therefore, $\Delta_n(\text{form}_{\text{C}=\text{C},\perp}; \text{meth}_{\text{C}=\text{C}})$ can be taken to represent $\Delta H_{\text{ind}}[(\text{form}_{\text{C}=\text{C}})_n]$. As n decreases from 3 to 1 (Table 2), this value increases from 9.3 kcal/mol to 17.8 kcal/mol. This dependence on n is expected, given that the distance between the $\text{HC}=\text{O}$ and the OH groups also decreases from $n = 3$ to $n = 1$.

$\Delta_n(\text{form}_{\text{C}=\text{C},\perp}; \text{meth}_{\text{C}=\text{C}})$ was extrapolated to $n = 0$, using a functional form in which the inductive contribution falls off exponentially with n . An exponential function was chosen following observations by Bianchi et al.,³³ in which NMR chemical shifts of the alkene carbons in $\text{H}_2\text{C}=\text{CH}(\text{CH}_2)_n\text{X}$ are dependent exponentially on n , for a number of different functional groups, X. The extrapolation to $n = 0$ yields a value of 24.2 ± 1.3 kcal/mol, suggesting that about 24 kcal/mol (about 62%) of the 39 kcal/mol acidity enhancement of formic acid over methanol are due to inductive effects and the remaining 15 kcal/mol (about 38%) are due to resonance effects. This extrapolation is in excellent agreement with the extrapolation of $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ to $n = 0$.

Our results are in excellent quantitative agreement with Rablen,²³ who concluded, using one model, that 80% of the enhanced acidity of acetic acid is due to inductive effects and 20% to resonance and, using another model, that inductive effects account for about $2/3$ of the enhanced acidity, while resonance accounts for the remaining $1/3$. Our results are also in agreement with Siggel et al.,¹⁶ who argued that inductive effects contribute 80% to the enhanced acidity, and with Taft et al., who concluded that inductive effects contribute about 70%. It is clear, however, that our results are in disagreement with the conclusions made by Dewar and Krull,⁹ who compared the calculated acidities of $(\text{form}_{\text{C}=\text{C}})_n$ with those of $(\text{vin}_{\text{C}=\text{C}})_n$ to conclude that the acidity enhancement of formic acid over methanol is almost entirely due to resonance effects. The remainder of the Discussion provides insight into this discrepancy.

Vinyl Alcohol versus Methanol. As with the formic acid vinyllogues, the difference in acidities between the vinyl alcohol vinyllogues with the $\text{CH}=\text{CH}_2$ group parallel and perpendicular to the remainder of the conjugated system (i.e., $\Delta_n(\text{vin}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C},\perp})$) represents $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$. Also, $\Delta_n(\text{vin}_{\text{C}=\text{C},\perp}; \text{meth}_{\text{C}=\text{C}})$ represents $\Delta H_{\text{ind}}[(\text{vin}_{\text{C}=\text{C}})_n]$. $\Delta_n(\text{vin}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C},\perp})$ increases with decreasing n (Table 2), from 4.8 kcal/mol at $n = 3$ to 8.8 kcal/mol at $n = 1$. $\Delta_n(\text{vin}_{\text{C}=\text{C},\perp}; \text{meth}_{\text{C}=\text{C}})$ also increases with decreasing n , from 3.3 kcal/mol at $n = 3$ to 6.4 kcal/mol at $n = 1$.

$\Delta H_{\text{ind}}[\text{vinyl alcohol}]$ was estimated by extrapolating $\Delta_n(\text{vin}_{\text{C}=\text{C},\perp}; \text{meth}_{\text{C}=\text{C}})$ to $n = 0$, using the same exponential functional form that was used for formic acid. This extrapolation yields 8.9 ± 1.0 kcal/mol, suggesting that about 9 kcal/mol of the acidity enhancement of vinyl alcohol over methanol are due to inductive effects and the remaining 17 kcal/mol are due to resonance effects.

We can estimate $\Delta H_{\text{res}}[\text{vinyl alcohol}]$ directly by extrapolating $\Delta_n(\text{vin}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C},\perp})$ to $n = 0$ using a linear functional form, as was done in the extrapolation of $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ to $n = 0$. Such an extrapolation yields 10.6 ± 0.5 kcal/mol.

(32) Brauman, J. I.; Blair, L. K. *J. Am. Chem. Soc.* **1970**, *92*, 5986.

(33) Bianchi, G.; Howarth, O. W.; Samuel, C. J.; Vlahov, G. *J. Chem. Soc., Perkin Trans. 2* **1995**, *7*, 1427–1432.

However, unlike the formic acid vinyllogues, $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\text{L}})$ is significantly dependent on n , and a linear extrapolation may be inappropriate. If we assume that the resonance contribution by the terminal vinyl group toward the acidity of $(\text{vin}_{\text{C}=\text{C}})_n$ is about the same as the other vinyl groups in the conjugated system, we can crudely approximate that $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$ is inversely proportional to $(n + 1)$, where n is defined as before as the total number of nonterminal vinyl groups in the conjugated system. This is because the resonance contribution by one vinyl group would be about $1/(n + 1)$ of the total resonance contribution by all of the vinyl groups in $(\text{vin}_{\text{C}=\text{C}})_n$. An extrapolation using this functional form yields 15.3 ± 6.1 kcal/mol at $n = 0$. This suggests that about 15 kcal/mol of the 26.2 kcal/mol acidity enhancement of vinyl alcohol over methanol are due to resonance effects and the remaining 11 kcal/mol are due to inductive effects; these results are consistent with the direct extrapolation of the inductive effects to $n = 0$ discussed previously.

Extrapolations of both the resonance and the inductive effects of the vinyl alcohol vinyllogues suggest that inductive effects in vinyl alcohol are significant—around 9–11 kcal/mol. This result is in accord with Bokman's results, which suggest that "the double bonds of the enols are polarized to give less negative potentials at the acidic protons (less strongly bound)."³⁴ It is also consistent with extra stabilization in the anion, as a result of both the polarizability of the π electrons and the greater effective electronegativity of the sp^2 hybridized carbons in the vinyl group over the sp^3 hybridized carbon in the methyl group.⁵ The notion that the vinyl group provides significant inductive effects on the acidity of vinyl alcohol, however, is in opposition to an assumption made by Dewar and Krull, which was central to their conclusions regarding the acidity of formic acid.

Our results are also in opposition to a second assumption that is part of Dewar and Krull's model—namely, the assumption that both $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ and $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$ are independent of n . Although it was not explicitly mentioned by Dewar and Krull, such an assumption must be made if the function of $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C}})$ on n is to reflect only the inductive effects in $(\text{form}_{\text{C}=\text{C}})_n$. Instead, the values in Table 2 suggest that whereas $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ is relatively independent of n , $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$ decreases significantly with n . Consequently, the lack of dependence of $\Delta_n(\text{form}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C}})$ on n , as originally observed by Dewar and Krull,⁹ appears to be an accidental cancellation of the different dependencies of $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ and $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$ on n . In light of these results, we revisit Dewar and Krull's model later in the Discussion.

It is interesting that $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ and $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$ have different dependencies on n . Although this phenomenon is not clearly understood, it can be rationalized, at least in part, by resonance theory. In the formate anion, resonance serves to distribute the negative charge on the two oxygen atoms (Figure 1a). The addition of a $\text{C}=\text{C}$ unit between the oxygen atoms will add a resonance structure in which the negative charge is on a carbon atom (Figure 5a). Because the charge in the added resonance structure is on a carbon atom, that resonance structure will be less important than those in which the negative charge is on an oxygen atom, given that a carbon atom has a smaller electronegativity than that of an oxygen atom. Therefore, the

importance of the resonance structure in which the negative charge is on the $\text{HC}=\text{O}$ group should not significantly change. This should also be true for each additional $\text{C}=\text{C}$ unit.

In the anion of vinyl alcohol, on the other hand, resonance serves to distribute the negative charge between the terminal carbon atom of the $\text{HC}=\text{CH}_2$ group and the oxygen atom. As with formic acid, the addition of a $\text{C}=\text{C}$ will add a resonance structure in which the negative charge is on a carbon atom (Figure 5b). The importance of this added resonance structure should be roughly equal to that of the resonance structure in which the negative charge is on the terminal carbon atom of the $\text{HC}=\text{CH}_2$ group. Therefore, the relative importance of the latter should decrease and should continue to decrease with each additional $\text{C}=\text{C}$ unit.

A natural population analysis of atomic charges supports these conclusions from resonance theory. Both the charge on the oxygen atom in the $\text{HC}=\text{O}$ group of the $(\text{form}_{\text{C}=\text{C}})_n$ anion and the charge on the terminal carbon atom in the $\text{HC}=\text{CH}_2$ group of the $(\text{vin}_{\text{C}=\text{C}})_n$ anion decrease with n (Table 3). That decrease is more dramatic for the latter, suggesting that the resonance contribution by the $\text{HC}=\text{CH}_2$ group toward the acidity of $(\text{vin}_{\text{C}=\text{C}})_n$ should have a greater dependence on n than the resonance contribution by the $\text{HC}=\text{O}$ group toward the acidity of $(\text{form}_{\text{C}=\text{C}})_n$.

Formic Acid versus Vinyl Alcohol. Formic acid is calculated to be about 12.8 kcal/mol more acidic than vinyl alcohol. The contributions by resonance and inductive effects toward this acidity enhancement can be derived from the resonance and inductive contributions toward the acidity enhancement of each acid over methanol. Specifically, $\Delta H_{\text{ind}}[\text{formic acid}]$ is about 24–25.5 kcal/mol and $\Delta H_{\text{ind}}[\text{vinyl alcohol}]$ is about 9–11 kcal/mol, suggesting that the bulk of the 12.8 kcal/mol acidity enhancement of formic acid over vinyl alcohol is due to a difference in inductive effects. This conclusion is consistent with the greater electronegativity of the oxygen atom in the $\text{HC}=\text{O}$ group of $(\text{form}_{\text{C}=\text{C}})_n$ than that of the terminal carbon atom of the $\text{HC}=\text{CH}_2$ group of $(\text{vin}_{\text{C}=\text{C}})_n$.

Dewar and Krull's Model Revisited. Our results suggest that $\Delta H_{\text{ind}}[\text{vinyl alcohol}]$ is about 9–11 kcal/mol. Furthermore, $\Delta H_{\text{res}}[(\text{vin}_{\text{C}=\text{C}})_n]$ is significantly dependent on n , whereas $\Delta H_{\text{res}}[(\text{form}_{\text{C}=\text{C}})_n]$ is not. Consequently, the function of $\Delta H_n(\text{form}_{\text{C}=\text{C}}; \text{vin}_{\text{C}=\text{C}})$ on n , observed by Dewar and Krull, does not reflect only the inductive contribution by the $\text{HC}=\text{O}$ group. A more logical functional group to compare against the $\text{HC}=\text{O}$ group would be the methyl group, because it does not contribute significantly via resonance or induction. Furthermore, as argued earlier, the resonance contribution of the $\text{HC}=\text{O}$ group toward the acidity of $(\text{form}_{\text{C}=\text{C}})_n$ is relatively independent of n . Therefore, as n increases, a decrease in $\Delta H_n(\text{form}_{\text{C}=\text{C}}; \text{meth}_{\text{C}=\text{C}})$ should essentially reflect only the attenuation of the inductive effects of the $\text{HC}=\text{O}$ group on the acidity of $(\text{form}_{\text{C}=\text{C}})_n$. At large n , the inductive effects should be absent; any residual acidity enhancement should therefore be a measure of $\Delta H_{\text{res}}[\text{formic acid}]$.

$\Delta H_n(\text{form}_{\text{C}=\text{C}}; \text{meth}_{\text{C}=\text{C}})$ decreases significantly with n (Table 2, Figures 6 and 7), from 39.0 kcal/mol at $n = 0$ to 20.4 kcal/mol at $n = 3$. Assuming an exponential decrease of the inductive effect with n ,³³ nonlinear regression suggests that $\Delta H_n(\text{form}_{\text{C}=\text{C}}; \text{meth}_{\text{C}=\text{C}})$ asymptotes to 11 ± 1 kcal/mol. This suggests that $\Delta H_{\text{res}}[\text{formic acid}]$ is roughly 11 kcal/mol and that

(34) Bokman, F. *J. Am. Chem. Soc.* **1999**, *121*, 11217–11222.

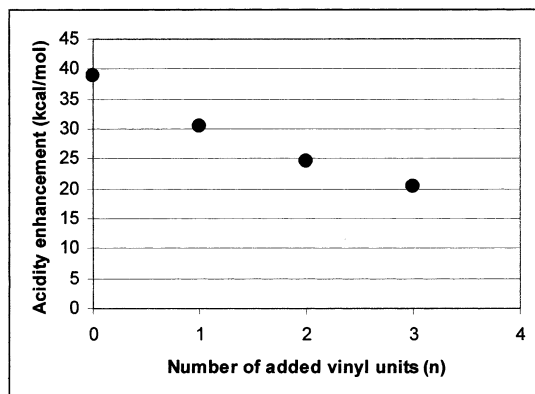


Figure 6. Calculated acidity enhancement (B3LYP/6-31+G*) of the formic acid vinylogues over the methanol vinylogues.

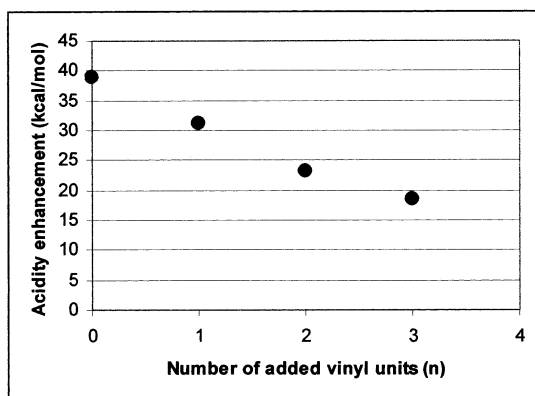


Figure 7. Calculated acidity enhancement (B3LYP/6-31+G*) of the formic acid alkynylogues over the methanol alkynylogues.

$\Delta H_{\text{ind}}[\text{formic acid}]$ is 28 kcal/mol. These figures are in good quantitative agreement with our results from extrapolating $\Delta H_n(\text{form}_{\text{C}=\text{C}}; \text{form}_{\text{C}=\text{C},\perp})$ and $\Delta H_n(\text{form}_{\text{C}=\text{C},\perp}; \text{meth}_{\text{C}=\text{C}})$ to $n = 0$.

A similar extrapolation of $\Delta H_n(\text{form}_{\text{C}=\text{C}}; \text{meth}_{\text{C}\equiv\text{C}})$ suggests that $\Delta H_{\text{res}}[\text{formic acid}]$ is -2 ± 14 kcal/mol. Although this negative value is not physically meaningful, and the uncertainty is large, this result is in qualitative agreement with the

extrapolation of the vinylogues, suggesting that inductive effects account for the majority of the acidity enhancement of formic acid over methanol.

Conclusion

Moderately high level density functional theory calculations were employed to calculate the acidity of formic acid, vinyl alcohol, and methanol, along with their vinylogues with as many as three added vinyl units. Acidities were also calculated for the formic acid and vinyl alcohol vinylogues with the formyl group and the terminal vinyl group, respectively, perpendicular to the rest of the conjugated system. Comparisons among these calculated acidities yielded measurements of resonance and inductive contributions toward the acidity enhancement of the formic acid vinylogues over corresponding methanol vinylogues, as well as of the vinyl alcohol vinylogues over corresponding methanol vinylogues. For each acid, the resonance and inductive contributions were separately extrapolated to $n = 0$, yielding the resonance and inductive contributions in the parent acids. In both cases, the separate extrapolations were self-consistent, suggesting that (1) inductive effects account for roughly 24–25.5 kcal/mol (62% to 65%) of the 39 kcal/mol calculated acidity enhancement of formic acid over methanol and the remaining 15–13.5 kcal/mol (38% to 35%) are due to resonance and (2) inductive effects account for about 9–11 kcal/mol of the 26 kcal/mol calculated acidity enhancement of vinyl alcohol over methanol and the remaining 17–15 kcal/mol are due to resonance.

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