larger decrease in the rate of hydride ion abstraction. Thus, there is a decrease in rate with increasing pH. Around neutral pH, the reaction proceeds mainly through path C in Scheme III. For the reasons stated earlier, there occurs a change in rate-limiting steps from the breakdown of the bromo ester (i.e., the k_2' step) to the disappearance of the imine (i.e., the k_3' and k_3'' steps). In the case of alanine and valine, the imine intermediate is converted into two sets of products by reacting with either water or by interacting with the oxidizing species. Of these, the reaction with water (i.e., the k_3' step) is an acid-catalyzed reaction and the other (i.e., the k_3'' step) is a base-catalyzed reaction. Hence, an increase in pH above the pk_a of the imine inhibits the reaction with water but enhances the interaction with the oxidizing species and causes a net increase in rate.

Conclusion

The mechanisms of oxidative decarboxylation of amino acids promoted by NBS have been shown to be significantly influenced by the presence of alkyl groups at the α-carbon. It will be interesting to see if this effect extends to other amino acids and to oxidizing agents other than NBS. It has been shown that the proton inventory technique can provide considerable information about the mechanisms of such oxidative decarboxylation reactions and its use in such studies should prove worthwhile.

Experimental Section

Materials. Glycine, glycine-d_5, alanine, DL-valine, citric acid, acetic acid, acetic acid-*d* (98 atom % D), glycine ethyl ester hydrochloride, and betaine hydrochloride (99%) were all commercial samples and were used as obtained. *N*-Bromosuccinimide (Aldrich) was recrystallized from water. Deuterium oxide (99.75 atom % D; Bio-Rad) was used as obtained. Water was twice glass distilled before use.

Citric acid–disodium hydrogen phosphate buffer solutions of desired pH were prepared by mixing the required volumes of stock solutions of 0.1 M citric acid and 0.2 M disodium hydrogen phosphate.

Acetic acid–sodium acetate buffer solutions of the desired pH(D) were prepared by mixing the required volumes of stock solutions of acetic acid (or acetic acid-*d*) and sodium acetate in protium oxide or deuterium oxide. The ionic strength of the stock solutions was maintained with sodium perchlorate at 0.5 M. Solutions of lower buffer concentration were prepared from the above buffer solution by dilution with 0.25 M sodium perchlorate solution. The pH(D) of the solutions was measured by using a Corning pH meter Model 130 equipped with a combination electrode.

Kinetics. The oxidative decarboxylations of glycine, alanine, and valine were monitored by following the decrease in absorbance at 240 nm on a Cary 118C UV–vis spectrophotometer equipped with a constant-temperature cell compartment and cell holder to maintain a constant temperature.

Reactions were initiated by injecting 25 μL of a stock solution of NBS in acetonitrile into 3.00 mL of the appropriate buffer solution containing the substrate. The runs were generally initiated exactly 75 s after the injection of the substrate solution. Reactions were followed to greater than 80% completion. Absorbance values at 5- or 10-s intervals were collected by using a Micromation computer interfaced to the Cary 118C spectrophotometer. The data were then analyzed by using a nonlinear least-squares computer program. Plots of log $(A_t - A_\infty)$ vs. time were used in a confirmatory fashion.

The reactions of alanine or valine with NBS (6×10^{-4} M) at pH 3.7 (acetic acid–sodium acetate buffer) at 25 °C exhibited no dependence on amino acid concentration over the range 0.6×10^{-2} to 18×10^{-2} M. The first-order rate constants were 5.54×10^{-2} s^{-1} and 1.54×10^{-2} s^{-1}, respectively, within experimental error. The concentration of NBS at pH 3.7 (ionic strength was 0.5 M) at 25 °C was varied from 1×10^{-4} to 8.4×10^{-4} M (glycine concentration was 1.22×10^{-2} M) and was shown to have no effect on the first-order rate constant for the oxidative decarboxylation of glycine ($k = 4.36 \times 10^{-3}$ s^{-1} within experimental error). Variation of the ionic strength from 0 to 0.28 M ($NaClO_4$) at pH 5 did not influence the rate constant ($k = 8.43 \times 10^{-3}$ s^{-1}) for the glycine decarboxylation.

Acknowledgment. Support of this research by the Robert A. Welch Foundation is gratefully acknowledged.

Registry No. Glycine, 56-40-6; DL-alanine, 302-72-7; DL-valine, 516-06-3; *N*-bromosuccinimide, 128-08-5.

Carbonyl Methylenation Using a Titanium–Aluminum (Tebbe) Complex[1]

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The titanium–aluminum (Tebbe) complex $[Cp_2TiCH_2ClAl(CH_3)_2]$ is shown to be an effective methylenating agent for a variety of carbonyl groups. The reaction is unique in that the carbonyl groups of carboxylic acid derivatives are readily methylenated. Thus vinyl enol ethers are prepared from esters and enamines are formed from amides. The complex provides a method for methylenating hindered or base sensitive ketones that is advantageous to the Wittig reagent. Selective methylenation of dicarbonyl compounds is also accomplished.

Methylenation and general alkylidenation of ketones and aldehydes using the Wittig reaction is well established in the methodology of organic synthesis.[3] There are, however some limitations to the use of the technique. Wittig reactions are quite sensitive to the steric environment around the carbonyl group undergoing reaction.[4] Further, the

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(2) (a) Participant in the NIH–MARC program. (b) Participant in the NIH–MBRS program. (c) Participant in the ACS–SEED program.

(3) (a) Maercker, A. *Org. React. (N.Y.)* **1965**, *14*, 270. (b) House, H. O. "Modern Synthetic Reactions"; Benjamin; Menlo Park, CA, 1972; pp 682–709. (c) Bestman, H. J.; Vostrowsky, O. *Top. Cur. Chem.* **1983**, *109*, 65.

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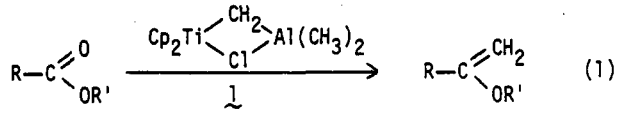
0022-3263/85/1950-1212$01.50/0

basic character of the ylide reagent is often incompatable with sensitive carbonyl-containing compounds.[3a,5] A notable restriction of the Wittig reaction is that it does not normally proceed with the carbonyl groups of carboxylic acid derivatives.[6]

We recently reported that the titanium–aluminum carbenoid complex **1**, initially studied by Tebbe and co-workers,[7] is an effective methylenating reagent for carboxylic acid esters.[8] The reaction provides a route to vinyl enol ethers from readily available esters (eq 1).



(1)

Cp = η^5-C_5H_5

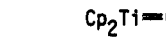
This "Wittig type" reaction by a transition-metal carbenoid complex has analogy in the alkylidenation reactions reported by Schrock and co-workers using tantalum and niobium complexes.[9] Those latter compounds have not proven to be of general utility in synthesis. Grubbs and co-workers have recently demonstrated that aluminum-free titanium metallacycles derived from **1** are also effective carbonyl alkylidenation reagents for a variety of carbonyl-containing compounds.[10] Schwartz,[11] Negishi,[12] and Yoshida[13] have reported carbonyl alkylidenations using related transition-metal complexes.

In the following we report an extention of the ester methylenation reaction[8] to include a variety of structurally diverse esters. We also demonstrate the effectiveness of **1** for the methylenation of ketone carbonyl groups and illustrate selective carbonyl methylenation of keto esters. Furthermore, we report that amides can be converted to enamines as another example of the generality of this carbonyl methylenation reaction.

Results and Discussion

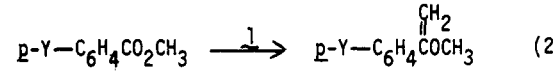
The titanium–aluminum complex is prepared by the method of Tebbe and co-workers[7] and is also available commercially. The deep maroon solids are sensitive to air, water, and other proton sources. They are soluble and stable in toluene or benzene (a suspected carcinogen—handle appropriately) and are readily handled by standard inert atmosphere techniques.[14] The general methylenation reaction involves addition of a solution of the complex **1** to a cold solution of the carbonyl compound in tetrahydrofuran (THF). After 0.5–1 h, the addition of dilute aqueous base or methanol followed by purification of the crude reaction mixture through a short column of basic alumina provides the desired product.

Esters. Carboxylic acid esters are readily converted to the corresponding vinyl enol ethers. Reactions are rapid when a Lewis base such as THF is present in the reaction mixture. When no added Lewis base is present, the ester oxygen atoms assume that function and the reactions are considerably slower. In those cases 4–12 h are typically required for completion of the methylenation. The Lewis base is believed to complex the aluminum and release the highly reactive titanium carbenoid intermediate **2**.[7,10b]



2

Structural variation in the ester appears to have only a minor effect on the methylenation yield. Thus a series of para-substituted methyl benzoates (**3a–d**) designed to investigate electronic effects on the reaction provides good yields of enol ether products **4a–d** in all cases (eq 2).

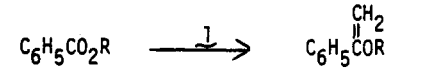


(2)

a, Y = H; **b**, Y = CH_3; **c**, Y = OCH_3; **d**, Y = Cl

Small rate differences are observed when reactions are carried out in the absence of added Lewis base,[15] but this has little effect on product yield.

Alteration in the alcohol portion of the ester does not normally affect product yield. The series of benzoates esters **3a**,**5a–c** reflect both steric and electronic change (eq 3). The *tert*-butyl ester **5d** reacts similarly; however,



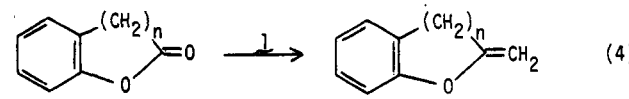
(3)

a, R = $CH(CH_3)_2$ **c**, R = C_6H_5

b, R = $CH_2C_6H_5$ **d**, R = $C(CH_3)_3$

diminished yields appear to be due to a combination of steric inhibition of the methylenation and competitive decomposition of **1**.

Lactones **7a**,**b** are also readily methylenated by **1** to produce *exo*-methylene oxygen heterocycles[8] (eq 4). Paquette and co-workers[16] have used the methylenation of unsaturated lactones to provide precursors for electrocyclic rearrangement pathways during natural product syntheses.



(4)

a, n = 1; **b**, n = 2

One potential problem in the synthetic utility of methylenation by the complex **1** is its possible interaction with carbon–carbon double bonds that might be present in the ester molecule. Complex **1** is an analogue of the Ziegler–Nata catalysts and was originally investigated as a potential alkene homologation catalyst.[7] Formation of tita-

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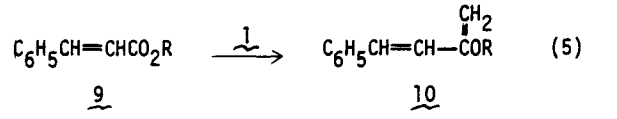
nium metallacycles from 1 plus alkene has been reported by Grubbs and co-workers.[10b,17]

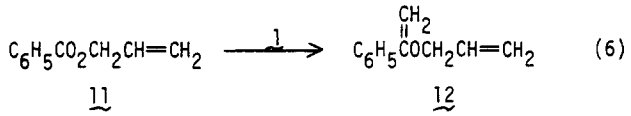
We were concerned that the reagent might interact competetively with the carbonyl and alkene double bonds. That has proven not to be a problem for substituted alkenes as demonstrated by the methylenations of unsaturated esters **9a–c** (eq 5). Furthermore, the stereochemical



(5)

integrity of the carbon–carbon double bond is maintained during the reaction as demonstrated by using both the *Z* and *E* isomers of **9b**.[8]

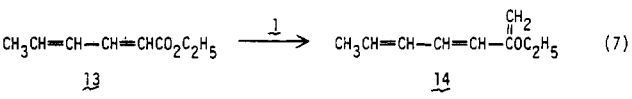
Interestingly, methylenation of the allyl ester **11** leads to only a moderate yield of the enol ether **12** (eq 6) plus



(6)

unreacted starting material. It appears that, in this case, **1** may interact with the terminal carbon–carbon double bond and is subsequently lost to the methylenation process.

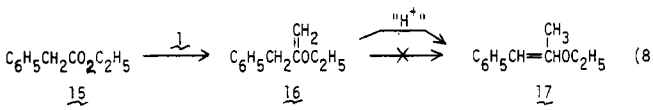
The methylenation of ethyl sorbate (**13**) provides an example of the possible utility of the ester methylenation to produce a 2-substituted triene **14** (eq 7) or related



(7)

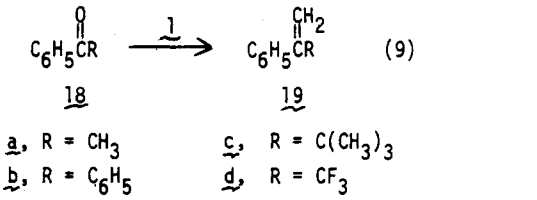
polyene, the potential precursor for an electrocyclic reaction. Stevenson and Bryson used such an approach to synthesize a 1,5-diene.[18]

The possibility was also investigated that the new carbon–carbon double bond might isomerize to a thermodynamically more stable position in the presence of the titanium and aluminum species from the complex. That was shown not to be a problem by using as examples the esters **7a** and **15**. In both cases, the more stable, conjugated product was not observed during the reaction. However, the conversion of **16** to **17** in the presence of a proton source did confirm the expected thermodynamic stabilities in that case (eq 8).



(8)

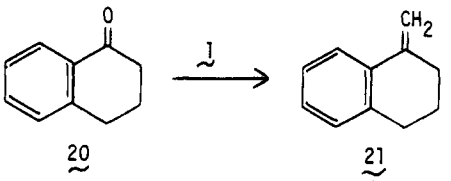
Ketones. Tebbe and co-workers reported the methylenation of cyclohexanone using **1**.[7] Although the Wittig and a variety of other reactions are useful for ketone methylenation reactions,[3,5d,19] the general importance of this conversion encouraged us to explore the possibility that complex **1** might complement those methods. A series of ketones (**18a–d**), dissolved in THF, toluene, or benzene was treated with **1** (eq 9). Methylenation was rapid in



(9)

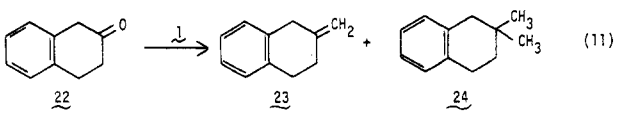
both the hydrocarbon and the Lewis base solvents, showing that ketone reactivity is greater than that of esters, a result similar to the well-established reactions of the carbonyl group with nucleophiles. Of interest is the observation that reactions proceed well with methyl **18a** as well as *tert*-butyl **18c** ketones.

Methylenation of 1-tetralone (**20**) (eq 10) proceeds with no problems from the peri interactions or enolization.



(10)

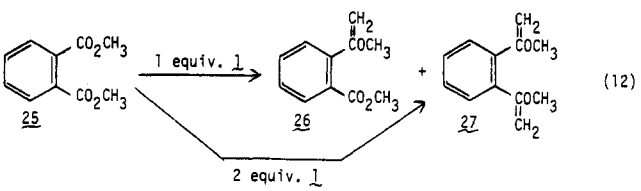
Methylenation of 2-tetralone (**22**) illustrates an interesting competitive reaction (eq 11). Reaction of equimolar



(11)

quantities of **22** and **1** leads to the expected methylenation product **23** along with 20–25% of **24**. The dimethylation product presumably results from the reaction of **23** with **1**. Grubbs and co-workers have observed related results in their work with titanium metallacycles.[10b,20]

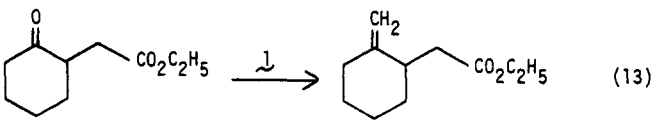
Dicarbonyl Compounds. The possibility that selective methylenation might occur using **1** was also explored. Thus, the diester, dimethyl phthalate (**25**), when treated with 1 equiv of **1** yields monomethylenation product **26** along with 20–30% of dimethylenation product **27** (eq 12).



(12)

The result reflects an approximate statistical methylenation of equivalent ester groups. When 2 equiv of complex are used, dimethylenation takes place to give only **27**.

The observation that ketone carbonyl groups react with **1** considerably faster than do ester carbonyl groups suggested that it might be possible to selectively methylenate only one carbonyl in a keto ester. Thus when **28** is treated with **1**, only **29**, the product of ketone methylenation, is observed (eq 13).



(13)

We have similarly found that a 1,2-keto ester (a pyruvate) can undergo selective mono- or dimethylenation using

(17) Howard, T. R.; Lee, J. B.; Grubbs, R. H. *J. Am. Chem. Soc.* **1980**, *102*, 6876.

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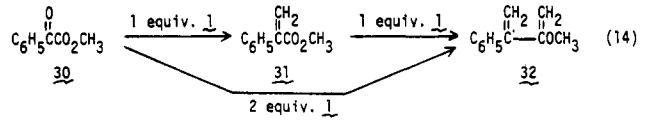
(20) Grubbs, R. H., unpublished results.

1. Thus **30** is converted to **31** with 1 equiv of 1 or to **32** with 2 equiv of 1 (eq 14). Diene **32** is related to the

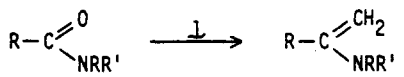


(14)

intermediates that have been used effectively by Danishefsky and co-workers as electrocyclic precursors in synthesis.[21]

We had previously shown that the opposite sequence, selective methylenation of the ester carbonyl of a keto ester, can be accomplished by the classical approach involving prior protection of the ketone carbonyl.[8] Dimethylenation of both carbonyl groups of a keto ester was also used as the route to a potential precursor for the steroid A–B ring structure.[8]

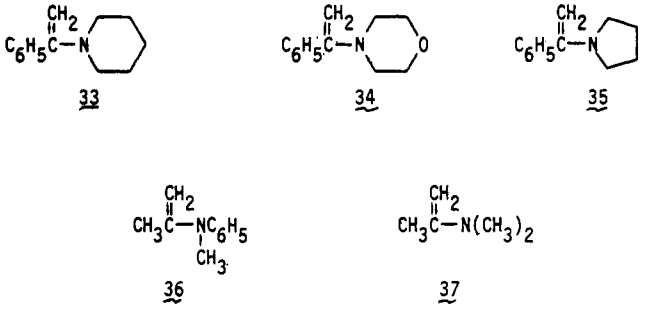
Amides. The methylenation of amides by 1 leads to enamines (eq 15). Reactions are rapid even without the



(15)

use of a Lewis base promoter. This suggests that the nitrogen atom of the amide carbonyl functions as the required base and is more effective than the oxygen atoms of an ester.

This reaction provides an attractive alternative to the classical enamine preparations[22] and specifically as a route to the enamines of methyl ketones as exemplified by **33–37**.



33 **34** **35**

36 **37**

The resultant enamines can be isolated or directly alkylated. Amide methylenation followed by enamine alkylation is a carbonyl alkylidenation equivalent, an alternative to the use of the still elusive homologues of 1.

Conclusion. The titanium–aluminum complex 1 has been found to be a general and effective methylenating reagent for the carbonyl group of ketones, esters, and amides. The reaction with ketones supplements the Wittig reaction and may be preferrable for those compounds with hindered carbonyl groups or that contain base-sensitive groups. Methylenation of carboxylic acid esters and amides is a new, synthetically useful reaction. The ability to use 1 to selectively methylenate a carbonyl group in dicarbonyl compounds extends the synthetic utility of the reaction. The extension of this reaction to other carboxylic acid derivatives is under investigation by ourselves and others.[10b,20]

Experimental Section

All reactions were carried out under conditions free of oxygen and moisture. Reaction solvents were purified by distillation from sodium benzophenone ketyl under nitrogen or argon. The complex 1 was normally handled as a solution in benzene or toluene. Exploratory NMR tube reactions were carried in perdeuteriobenzene. NMR spectra were obtained on a Varian EM-390 spectrometer.

Method A. To a solution of 1 mmol of carbonyl compound in 2–3 mL of tetrahydrofuran (usually cooled to 0 °C) is added 2 mL of ca. 0.5 M complex 1[7] in toluene or benzene (a suspectected carcinogen; handle accordingly). After about 30 min 10–20 mL of ether is added, and then 5–10 drops of aqueous base (ca. 0.1 M NaOH) is slowly added with swirling to destroy active aluminum compounds. The deep red reaction mixture is dried with anhydrous sodium sulfate, filtered with Celite to enhance separation of the solids, and concentrated. Purification of the product is accomplished by chromatography on basic alumina using 2–5% ether in pentene as eluent. In many cases, rapid "filtration" of the crude product through a short column of basic alumina using ether as eluent is sufficient to purify the desired product. The conjugated dienes and enamines are only moderately stable to the chromatographic purification. Product recovery is enhanced by saturating the chromatography eluent with trimethylamine.

Method B. Similar to method A except that anhyrous methanol is used in place of aqueous sodium hydroxide to precipitate titanium and aluminum compounds. This is useful for water-sensitive compounds.

Method C. Similar to method A except that the complex solution is *freshly* prepared in dichloromethane. This ensures that solvents are easily removed and minimizes loss of volitile products. Vacuum transfer can also be used in these cases.

Method D. Dissolve 2×10^{-4} mol of 1 in 0.5 mL of C_6D_6. Add an equimolar quantity of the amide and of toluene as an internal standard. Follow the reaction by NMR.

1-Methoxy-1-phenylethene (4a):[8,23] method A, 81%; ^{1}H NMR ($CDCl_3$) δ 3.70 (s, 3), 4.20 (d, 1, J = 2 Hz), 4.60 (d, 1, J = 2 Hz), 7.2–7.7 (m, 5).

1-Methoxy-1-(*p*-methylphenyl)ethene (4b): method A, 93%; ^{1}H NMR (CCl_4) δ 2.3 (s, 3), 3.65 (s, 3), 4.0 (d, 1, J = 2 Hz), 4.5 (d, 1, J = 2 Hz), 6.7–7.5 (m, 4). Anal. ($C_{10}H_{12}O$) C, H.

1-Methoxy-1-(*p*-methoxyphenyl)ethene (4c): method B, 80%; ^{1}H NMR (CCl_4) δ 3.05 (s, 3), 3.65 (s, 3), 3.95 (d, 1, J = 2 Hz), 4.35 (d, 1, J = 2 Hz), 7.1–7.5 (m, 4). Anal. ($C_{10}H_{12}O_2$) C, H.

1-(*p*-Chlorophenyl)-1-methoxyethene (4d): method B, 76%; ^{1}H NMR (CCl_4) δ 3.6 (s, 3), 4.1 d, 1, J = 2 Hz), 4.5 (d, 1, J = 2 Hz), 7.0–7.5 (m, 4). Anal. (C_9H_9ClO) C, H.

1-Isopropoxy-1-phenylethene (6a): method B, 88%; ^{1}H NMR (CCl_4) δ 1.3 (d, 6, J = 7 Hz), 4.0 (d, 1, J = 2 Hz), 4.3 (m, 1, J = 7 Hz), 4.55 (d, 1, J = 2 Hz), 7.0–7.5 (m, 5). Anal. ($C_{11}H_{14}O$) C, H.

1-Benzoxy-1-phenylethene (6b): method B, 84%; ^{1}H NMR (CCl_4) δ 4.1 (d, 1, J = 3 Hz), 4.5 (d, 1, J = 3 Hz), 4.8 (s, 2), 7.0–7.6 (m, 10). Anal. ($C_{15}H_{14}O$) C, H.

1-Phenoxy-1-phenylethene (6c): method A, 94%; ^{1}H NMR (CCl_4) δ 4.25 (d, 1, J = 2 Hz), 4.85 (d, 1, J = 2 Hz), 6.8–7.6 (m, 10). Anal. ($C_{14}H_{12}O$) mass spectrum.

1-*tert*-Butoxy-1-phenylethene (6d): method A, 57%; separated from strating material by chromatography; ^{1}H NMR (CCl_4) δ 1.35 (s, 9), 4.3 (d, 1, J = 2 Hz), 4.7 (d, 1, J = 2 Hz), 6.9–7.4 (m, 5). Anal. ($C_{12}H_{16}O$) C, H.

2-Methylene-2,3-dihydrobenzofuran (8a):[8] method A, 85%; ^{1}H NMR ($CDCl_3$) δ 3.8 (br, 2), 4.2 (m, 1), 4.6 (m, 1), 6.7–7.2 (m, 4).

2-Methylene-3,4-dihydrobenzopyran (8b): method A, 85%; ^{1}H NMR (CCl_4) δ 2.3–2.8 (m 4), 3.95 (s, 1), 4.4 (s, 1), 6.5–7.1 (m 4). Anal. ($C_{10}H_{10}O$) mass spectrum.

3-Methoxy-1-phenyl-1,3-butadiene (10a): method B, 99%; ^{1}H NMR (CCl_4) δ 3.6 (s, 3), 4.1 (s, 2), 6.1–6.9 (AB mult, 2), 7.0–7.4 (m, 5). Anal. ($C_{11}H_{12}O$) C, H.

3-Ethoxy-1-phenyl-1,3-butadiene (10b):[8] method A, 80%; ^{1}H NMR ($CDCl_3$) δ 1.4 (t, 3, J = 6 Hz), 3.8 (q, 2, J = 6 Hz), 4.2 (s, 2), 6.4–7.0 (AB mult, 2), 7.1–7.5 (m, 5).

3-Benzoxy-1-phenyl-1,3-butadiene (10c): method B, 82%; ^{1}H NMR (CCl_4) δ 4.2 (s, 2), 4.75 (s, 2), 6.3–7.0 (AB mult, 2), 7.0–7.4 (m, 10). Anal. ($C_{17}H_{16}O$) C, H.

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1-Phenyl-1-(3-propenoxy)ethene (12): method A, 50%; ^{1}H NMR (CCl_4) δ 4.15 (d, 1, J = 3 Hz), 4.4 (m, 2), 4.65 (d, 1, J = 3 Hz), 5.1-5.6 (m, 2), 5.8-6.3 (m, 1), 6.2-6.8 (m, 5). Anal. ($C_{11}H_{12}O$) C, H.

2-Ethoxy-1,3,5-heptatriene (14): method A, 54%; ^{1}H NMR (CCl_4) δ 1.35 (t, 3, J = 7 Hz), 1.75 (d, 3, J = 5 Hz), 3.75 (q, 2, J = 7 Hz), 3.95 (s, 2), 5.4-6.6 (m, 4). Anal. ($C_9H_{14}O$) C, H.

2-Ethoxy-3-phenylpropene (16):[8] method A, 90%; ^{1}H NMR ($CDCl_3$) δ 1.2 (t, 3, J = 8 Hz), 3.3 (s, 2), 3.7 (q, 2, J = 8 Hz), 3.8 (d, 1, J = 2 Hz), 3.9 (d, 1, J = 2 Hz), 7.2 (s, 5).

2-Ethoxy-1-phenylpropene (17):[24] from isomerization of **16** in $CDCl_3$ to give 83% of a mixture of 70% *E* and 30% *Z* isomers; ^{1}H NMR ($CDCl_3$) δ 1.3 (t, 3, J = 7 HZ), 1.9 (s, 3), 3.75 (q, 2, J = 7 Hz), 5.2 (s, 0.3), 5.5 (s, 0.7), 6.8-7.3 (m, 5).

1-Methyl-1-phenylethene (19a):[25] method A, 88%; ^{1}H NMR (CCl_4) δ 2.05 (s, 3), 4.95 (br s, 1), 5.25 (br s, 1), 7.0-7.4 (m, 5).

1,1-Diphenylethene (19b):[26] method A, 97%; ^{1}H NMR (CCl_4) δ 5.3 (s, 2), 7.1 (s, 10).

3,3-Dimethyl-2-phenyl-1-butene (19c): method A, 96%; ^{1}H NMR (CCl_4) δ 1.1 (s, 9), 4.65 (d, 1, J = 2 Hz), 5.05 (d, 1, J = 2 Hz), 6.8-7.1 (m, 5). Anal. ($C_{12}H_{16}$) mass spectrum.

3,3,3-Trifluoro-2-phenylpropene (19d): method A, 50%; ^{1}H NMR (CCl_4) δ 5.6 (d, 1, J = 1 Hz), 5.8 (d, 1, J = 1 Hz), 7.2 (s, 5). Anal. ($C_9H_7F_3$) mass spectrum.

1-Methylene-1,2,3,4-tetrahydronaphthalene (21):[27] method A, 73%; ^{1}H NMR (CCl_4) δ 1.8 (m, 2), 2.5 (m, 2), 2.8 (t, 2, J = 6 Hz), 4.8 (d, 1, J = 1 Hz), 5.3 (d, 1, J = 1 Hz), 6.9 (m, 3), 7.5 (m, 1).

2-Methylene-1,2,3,4-tetrahydronaphthalene (23):[28] method A, 40%, separated from **24** via chromatography; ^{1}H NMR (CCl_4) δ 2.45 (t, 2, J = 7 Hz), 2.85 (t, 2, J = 7 Hz), 3.5 (s, 2), 4.75 (br s, 2), 6.9 (s, 4).

2,2-Dimethyl-1,2,3,4-tetrahydronaphthalene (24):[29] method A, 15%, separated from **23** via chromatography; ^{1}H NMR (CCl_4) δ 0.95 (s, 6), 1.5 (t, 2, J = 6 Hz), 2.45 (s, 2), 2.7 (t, 2, J = 6 Hz), 6.8 (br s, 4).

Methyl 2-(1-methoxyethenyl)benzoate (26): method A, 45%, separated from **27** via chromatography; ^{1}H NMR (CCl_4) δ 3.55 (s, 3), 3.7 (s, 3), 4.1 (d, 1, J = 2 Hz), 4.2 (d, 1, J = 2 Hz), 7.0-7.4 (m, 3), 7.4-7.6 (m, 1). Anal. ($C_{11}H_{12}O_3$) C, H.

1,2-Bis(1-methoxyethenyl)benzene (27): method A, 65%, using 2 equiv of **1**; ^{1}H NMR (CCl_4) δ 3.5 (s, 6), 4.1 (d, 2, J = 2 Hz), 4.2 (d, 2, J = 2 Hz), 6.9-7.3 (m, 4). Anal. ($C_{12}H_{14}O_2$) C, H.

Ethyl 2-(2-methylenecyclohexyl)acetate (29): method A, 67%; ^{1}H NMR (CCl_4) δ 1.15 (t, 3, J = 7 Hz), 1.4-2.6 (m, 11), 4.0 (q, 2, J = 7 Hz), 4.4 (s, 1), 4.5 (s, 1). Anal. ($C_{11}H_{18}O_2$) mass spectrum.

Methyl 2-phenyl-2-propenoate (31): method A, 72%; ^{1}H NMR (CCl_4) δ 3.7 (s, 3), 5.7 (d, 1 J = 1 Hz), 6.2 (d, 1, J = 1 Hz) 7.1-7.4 (m, 5). Anal. ($C_{10}H_{10}O_2$) mass spectrum.

2-Methoxy-3-phenyl-1,3-butadiene (32): method A, 45%; ^{1}H NMR (CCl_4) δ 3.6 (s, 3), 4.0 (d, 1, J = 2 Hz), 4.1 (br s, 1), 5.05 (br s, 1), 5.55 (d, 1, J = 2 Hz), 7.1 (s, 5). Anal. ($C_{11}H_{12}O$) mass spectrum.

1-(1-Phenylethenyl)piperidine (33):[30] method B, D, 76% (by NMR); ^{1}H NMR (CCl_4) δ 1.6 (m, 6), 2.8 (m, 4), 4.0 (s, 1), 4.1 (s, 1), 7.1-7.4 (m, 5). Anal. ($C_{13}H_{17}N$) mass spectrum.

4-(1-Phenylethenyl)morpholine (34):[31] method D, 67% (by NMR); ^{1}H NMR (C_6D_6) δ 2.8 (m, 4), 3.7 (m, 4), 4.3 (s, 1), 4.6 (s, 1), 7.0-7.8 (m, 5). Anal. ($C_{12}H_{15}NO$) mass spectrum.

1-(1-Phenylethenyl)pyrrolidine (35):[30] method D, 80% (by NMR); ^{1}H NMR (C_6D_6) δ 1.7 (m, 4), 3.1 (m, 4), 4.2 (s, 1), 4.35 (s, 1), 7.1-7.8 (m, 5).

***N*-Methyl-*N*-2-propenylbenzenamine (36)**:[32] method D, 97% (by NMR); ^{1}H NMR (C_6D_6) δ 1.9 (s, 3), 3.0, (s, 3), 4.3 (s, 1), 4.35 (s, 1), 6.9-7.4 (m, 5).

***N*-*N*-Dimethyl-2-propenamine (37)**:[32] method D; ^{1}H NMR (C_6D_6) δ 1.9 (s, 3), 2.6 (s, 6), 3.85 (s, 1), 3.95 (s, 1).

Registry No. **1**, 67719-69-1; **2a**, 93-58-3; **3b**, 99-75-2; **3c**, 121-98-2; **3d**, 1126-46-1; **4a**, 4747-13-1; **4b**, 51440-57-4; **4c**, 51440-56-3; **4d**, 67471-39-0; **5a**, 939-48-0; **5b**, 120-51-4; **5c**, 93-99-2; **5d**, 774-65-2; **6a**, 42237-98-9; **6b**, 25109-98-2; **6c**, 19928-57-5; **6d**, 78386-38-6; **7a**, 553-86-6; **7b**, 119-84-6; **8a**, 74104-12-4; **8b**, 74104-13-5; **9a**, 103-26-4; **9b**, 103-36-6; **9c**, 103-41-3; **10a**, 95045-97-9; **10b**, 77882-39-4; **10c**, 95045-98-0; **11**, 583-04-0; **12**, 40815-73-4; **13**, 2396-84-1; **14**, 95045-99-1; **15**, 101-97-3; **16**, 74104-11-3; (*E*)-**17**, 71094-33-2; (*Z*)-**17**, 71094-47-8; **18a**, 98-86-2; **18b**, 119-61-9; **18c**, 938-16-9; **18d**, 434-45-7; **19a**, 98-83-9; **19b**, 530-48-3; **19c**, 5676-29-9; **19d**, 384-64-5; **20**, 529-34-0; **21**, 25108-63-8; **22**, 530-93-8; **23**, 66448-77-9; **24**, 13556-55-3; **25**, 131-11-3; **26**, 51440-54-1; **27**, 95046-00-7; **28**, 24731-17-7; **29**, 53544-45-9; **30**, 15206-55-0; **31**, 1865-29-8; **32**, 95046-01-8; **33**, 14990-66-0; **34**, 7196-01-2; **35**, 3433-56-5; **36**, 21267-55-0; **37**, 22499-75-8; *N*-methylacetanilide, 579-10-2; 4-benzoylmorpholine, 1468-28-6; 1-benzoylpyrrolidine, 3389-54-6; dimethylacetamide, 127-19-5; 1-benzoylpiperidine, 776-75-0.

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Solvent Effects on Keto-Enol Equilibria: Tests of Quantitative Models

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The effect of solvent on the equilibrium constants between selected keto-enol isomer pairs has been determined. The protomeric systems studied are 5,5-dimethyl-1,3-cyclohexanedione (**1**), 2-methyl-1,3-cyclohexanedione (**3**), 3-oxabicyclo[4.3.0]-2,9-dioxononane (**5**), 2,4-pentanedione (**7**), ethyl 3-oxobutanoate (**9**), and 9-anthracenone (**11**). A wide variety of theoretical and empirical solvation parameters have been tested in a multiparameter linear free energy format to model the changes in equilibria. The most successful correlations are obtained with the Kamlet-Taft polarity-polarizability and hydrogen-bonding terms, although the Swain *A* and *B* factors have advantages in some cases. In general, for the isomer pairs in which the enol cannot form an internal hydrogen bond (**1-2**, **3-4**, and **11-12**), the equilibria appear to be controlled almost completely by the hydrogen-bonding basicity of the solvent. For the isomer pairs **5-6**, **7-8**, and **9-10**, in which intramolecular hydrogen bonding is possible, the polarity-polarizability effect dominates, although differential stabilization of the isomers by hydrogen bonding remains significant.

The effect of solvent on the relative energies of hydroxypyridine-pyridone and mercaptopyridine-thiopyridone isomers is quantitatively correlated by an approach that models the differential interactions of the

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