Micelles form readily with such branched surfactants in line with the "loose" Menger micelle. It is not clear, however, how branched surfactants would ever be able to form Fromherz micelles with their rigid parallel chains. The second point relates to the data in Table I. The Fromherz micelle can in no way accommodate our observation that chain termini are randomly distributed throughout the micelle. In summary, we must warn chemists (as was done about 50 years ago with regard to the Hartley micelle[30]) to view the Dill-Flory and Fromherz micelles for what they are: useful, perhaps ingenious, models that must not be taken literally with anionic micelles of small radii.[31]

Acknowledgment. This work was supported by the National Science Foundation and the donors of the Petroleum Research Fund, administered by the American Chemical Society.

Registry No. $KMnO_4$, 7722-64-7; *trans*-$CH_3CH_2CH{=}CHCH_2COOH$, 1577-18-0; *cis*-$CH_3CH_2CH{=}CHCH_2COOH$, 1775-43-5; $CH_2{=}CHCH_2CH_2COOH$, 591-80-0; $CH_2{=}CH(CH_2)_8COOH$, 112-38-9; *cis*-$CH_3(CH_2)_5CH{=}CH(CH_2)_7COOH$, 373-49-9; *cis*-$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$, 112-80-1; *cis*-$CH_3(CH_2)_4CH{=}CH(CH_2)_7COOH$, 506-17-2; SDS, 151-21-3; Myr, 13429-27-1; cyclohexene, 110-83-8; permanganate, 14333-13-2.

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(31) **Note Added in Proof**: A recent article entitled The Effect of a Terminal Double Bond on the Micellization of a Simple Ionic Surfactant concludes that a "terminal double bond does not display a significant tendency to act as a second headgroup". See: Spragne, E. D.; Dneker, D. C.; Larrabee, C. E. *J. Colloid Interface Sci.* **1983**, *92*, 416.

Variation of Steric Effects in Metal Ion Catalyzed Proton Transfer. A Probe of Transition-State Structure

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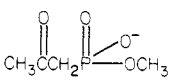
Abstract: The enolization of methyl 2-oxo-1-phosphonopropane (methyl acetonylphosphonate, MAcP) is catalyzed by pyridine bases in water. The catalysis is enhanced by dissolved magnesium ion or manganese ion. It is known that the metals form complexes via the phosphonate functional group of the substrate but promote catalysis by coordination to the carbonyl group. The rate of enolization is first order in substrate concentration and Brønsted base concentration. The rate is first order in metal ion concentration at low concentrations, changing to zero-order dependence (saturation) at higher levels. This saturation is used to obtain association constants: 33 M^{-1} (MAcP and magnesium ion), 7.5 M^{-1} (MAcP and manganese ion). The slope of the Brønsted plot for catalysis by unhindered pyridine bases in the absence of divalent metal ions is 0.69. The slope is 0.63 for reactions of the magnesium complex of MAcP and 0.82 for the manganese complex. The increase in slope with manganese catalysis appears to be inconsistent with the expectation from the reactivity-selectivity principle that acidification of the substrate will lead to an earlier transition state. Steric effects give further information about the catalytic systems. The rate constant for 2,6-lutidine falls on the Brønsted line for the manganese complex of MAcP but is a factor of 36 below the line in the uncomplexed case. The effect in the magnesium case is reduced to an intermediate value. This decreased steric effect suggests that the proton transfer transition state in the presence of the metal ions is significantly different from that in the absence of metal. It is proposed that coordination to divalent metal ions may provide a route by which a coordinated water molecule serves as a proton carrier for the very hindered base. These results show that steric effects are a valuable adjunct to Brønsted plots in multiple catalytic systems.

The conversion of a carbonyl compound to the corresponding enol is an important part of many complex organic and biological reactions. Mechanisms by which the reaction can be catalyzed by Brønsted acids and bases have been studied extensively.[1] In many biological systems, enolization is also promoted by metal ions which appear to act as catalysts by functioning as Lewis acids in conjunction with a Brønsted base.[2-5] This catalysis involves coordination of the metal ion to the carbonyl group during the step in which a proton is removed from the adjacent carbon atom by the Brønsted base or an intervening water molecule. Cox has recognized that the mechanism is analogous to that of the general acid catalyzed enolization of ketones involving a specific acid-general base mechanism.[6,7]



MAcP

We previously have studied examples of metal—catalyzed enolization reactions and have established the basic kinetic patterns of the combined metal ion-Brønsted base catalytic system.[8,9] In those studies we have used the monomethyl ester of acetonylphosphonic acid (MAcP) as a substrate for studies of the enolization reaction.[10] The phosphonate monoester functional group serves as a binding site for divalent metal ions which can serve as catalysts for reactions at the nearby carbonyl group (by a minor change in coordination).[2] This stabilizes an incipient enolate that is formed during the course of a reaction. The catalytic function of the metal ion also includes an electrostatic component in which a positively charged metal catalyst minimizes repulsions between reacting anions.[9]

It has been shown by Feather and Gold[11] and by Covitz and

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Westheimer[12] that general base catalyzed enolization reactions are subject to steric effects resulting from substituents adjacent to the basic site of a catalyst. Hine and his co-workers have analyzed similar kinetic results using molecular mechanics calculations.[13] The results of this type of analysis provide information on the nature of the transition state for the proton transfer process in enolization reactions. The conclusion that is most consistent with all the data is that sterically hindered bases participate in proton transfer reactions by transition states that involve the same angle of approach between reactants as in the case of unhindered bases.

We have now found that steric effects also can be used as a direct probe of the structure of the transition state of metal ion catalyzed proton transfer reactions from MAcP to neutral bases. Acceleration factors and Brønsted plots for a series of unhindered bases serve as a source for comparison of steric effects in the metal-catalyzed systems.

Experimental Section

Materials. Sodium methyl acetonylphosphonate was prepared following the procedure reported by Kluger.[10] All pyridine bases were obtained from Aldrich or from Eastman Kodak. All were distilled and redistilled. The bases 4-picoline, 2,4-lutidine, and 2,6-lutidine were further purified as complexes.[14,15] The purity of the bases was measured first by ^{1}H NMR spectroscopy (Varian T-60) and further by GLC analysis (Hewlett-Packard 5700, $^1/_8$ in. × 5 ft, 3% DEGS on Chromasorb W, 100–120 mesh at 70 °C). Magnesium(II) and manganese(II) were introduced as aqueous solutions of reagent grade magnesium sulfate and manganese chloride. Other inorganic materials were high quality commercially available materials which were used without further purification.

Kinetic Methods. Aqueous solutions of the pyridine derivatives were titrated to the required solution pH (= to the pK_a of the conjugate acid of that base) with 0.1 M HCl or 0.1 M NaOH. The solution pH was determined with a Radiometer pH Meter 28 using a GK2321C combined electrode or with a Fisher 119 combination meter, calibrated against "Fisher Certified" buffers at 35 °C.

The enolization of methyl acetonylphosphonate was followed by the rate at which iodine was taken up by the enol under conditions in which conversion of the ketone to the enol is rate determining.[9] The measurement of iodine decrease was done using the intermediate formation of triiodide ion as has been reported.[9] The decrease in absorbance due to triiodide disappearance during the course of the reaction was followed at 353 nm with a Coleman 124 double beam UV-visible spectrophotometer or a Cary 210 spectrophotometer interfaced to a Commodore 2001 computer, using the program we have developed called "Cary Disk". Data for each run were used to determine the best least-squares straight line ($r > 0.99$) for the initial reaction. All reactions were carried out in cells of 1-cm path length. All kinetic experiments were done at least in duplicate and reported results are mean values. Observed zero-order rates of iodine disappearance were converted to observed first—order rate constants (k_{obsd}) by dividing the total substrate concentration: $v = -d[I_2]/dT = k_{obsd}[SH]_t$. The basis of this equation is presented in the Results section.

Reactions studied in the absence of divalent metal ions were conducted at an ionic strength of approximately 0.1. Typically, 2.75 mL of 0.1 M potassium chloride and 0.1 mL of 1.57×10^{-3} M iodine in 0.3 M potassium iodide solution were added to a cuvette. The cell was placed in the temperature-regulated sample compartment of the spectrophotometer. Temperature was controlled to ±0.2 °C by a Neslab circulator. Sample temperature was monitored with a Fisher 119 combination meter with a Yellow Springs 700 probe. Samples were equilibrated at 35 °C (the reaction temperature) for approximately 3 min. A solution (0.1 mL) of pH-adjusted organic base was added (@35 °C). Then, 0.1 mL of 0.05 M methyl acetonylphosphonate (@35 °C) was added. The cell was shaken and the decrease in absorbance with time was recorded on a Heath recorder when the Coleman spectrophotometer was used or accumulated in the computer when the Cary spectrophotometer was used.

Reactions studied in the presence of divalent metal ions were run as follows. Potassium chloride solution (2.65 mL, 0.3 M) with 0.1 mL of 0.5 M magnesium sulfate was used for magnesium ion solutions. For manganese ion solutions, the reaction solution was obtained by combining 2.65 mL of 0.4 M potassium chloride with 0.1 mL of 0.5 M manganese chloride. The ionic strength in magnesium ion solutions was 0.3 and in manganese ion solutions was 0.4. (Increasing the ionic strength of the reaction solutions to 1.0 M did not affect the observed rate in several control samples so it is assumed that the differences in results for the two systems are not due to differences in ionic strength). These stock solutions were combined with iodine solution in the spectrophotometer cell, followed by the base and methyl acetonylphosphonate solutions. The absorbance decrease with time was recorded.

Stability Constants. The association constant for magnesium ion and monomethyl phosphonate esters has been shown to be in the range of 1 M^{-1} to 100 M^{-1} at pH 8.[16] However, the methods for the equilibrium measurements are not particularly precise. Because the metal ion complexed substrate is more reactive toward enolization than is the uncomplexed substrate,[9] we used a kinetic procedure to determine empirical stability constants to be used for the conditions of our reactions. The rate of enolization of the substrate was measured as a function of metal ion concentration. On the basis of equations presented in the Results section, affinity constants could be determined from a relationship between rate and metal ion concentration at constant substrate and base concentration. Due to the relatively low affinity of manganese for MAcP, concentrations up to 0.4 M metal ion were used and ionic strength was maintained at 1.0.

Although lutidines and picolines react with iodine,[17] these reactions are much slower than the reactions measured in our study. Incubation of the catalytic base in the iodine/iodide solutions never caused an observable reaction (no change in iodine absorbance) over the time range of the kinetic experiments. Since initial rate methods were used, complications due to slow side reactions competing near the end of reactions were avoided. The affinity of magnesium ion and manganese ion for pyridine derivatives is very low.[18] Furthermore, if complexes of the metal ions and bases formed, these would cause a rate depression, rather than the accelerations which we observe. Our results are also comparable with those that were obtained by NMR analysis of the deuteration of the same substrate,[2] indicating that the iodine procedure is not introducing artifacts.

Table I. Rate Constants for the Iodination of Methyl Acetonylphosphonate at 35 °C, Following Eq 1–12 for Scheme I[a]

base	pK_a[b]	k_b	k_b^{Mg}	k_b^{Mn}
pyridine	5.18	0.164	0.31	1.45
3-picoline	5.68	0.282	0.437	2.69
2-picoline	5.97	0.279	0.344	2.22
4-picoline	6.02	0.553	1.01	4.06
3,5-lutidine	6.14	1.01	1.15	9.65
3,4-lutidine	6.52	1.17	1.96	17.55
2,4-lutidine	6.72	0.873	1.12	19.66
2,6-lutidine	6.77	0.0542	0.282	22.88

[a] Units of rate constants are M^{-1} min^{-1}. [b] pK_a values are for the conjugate acids of the listed bases. The values used are from literature compilations cited in ref 9, 11, 14, and 15.

Results

The enolization of MAcP is accelerated by Brønsted bases and by magnesium and manganese ions. The data obtained by monitoring the initial rate of iodination of MAcP are summarized in Table I. Sterically hindered pyridine derivatives in most situations react more slowly than bases of comparable basicity.

Our data can be analyzed in terms of a mechanism in which both the substrate and its complex with a metal ion are subject to general base catalysts, as summarized in Scheme I. The uncomplexed substrate is represented as SH^-, the enolate is S^{2-}, and the complex of the substrate and metal is $SH^-{\cdot}M$. K^m is the association constant for each metal with the substrate. The rate constants are specified for each metal ion and base separately. The superscript "m" is replaced by either "Mg" or "Mn" as appropriate.

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Scheme I

$$SH^- + M \overset{K^m}{\rightleftharpoons} SH^-\cdot M$$

$$SH^-\cdot M + B \xrightarrow{k_b^m} S^{2-} + M + BH^+$$

$$SH^- + B \xrightarrow{k_b} S^{2-} + BH^+$$

$$S^{2-} + I_2 \xrightarrow{\text{fast}} SI^- + I^-$$

The disappearance of iodine occurs in a rapid step after rate-determining enolate formation has occurred, under the conditions of our study. We determined the rate constant for enolization of MAcP in the absence of buffer and metal by extrapolation of the observed buffer-dependent rate constants to that for a buffer concentration of zero. These points were used to fit a pH–rate profile to obtain rate constants k_o (the rate constant for water-catalyzed enolization) and k_{OH} (the rate constant for hydroxide ion catalysis of enolization) in the absence of metal ion, and the corresponding terms k_o^m and k_{OH}^m for each metal. The k_o and k_o^m values are subject to uncertainty since contributions by these terms are small over the pH range we studied. It was also determined that the reaction is first order in substrate and base (by variation of substrate concentration and base concentration). The observed values for the system in the absence of metal and the magnesium ion catalyzed reaction have been reported previously[9] and our results agree to the extent of the accuracy of the data with the values in that study. (However, there is a calculation error in the earlier work; the reported rate constants should be divided by the substrate concentration). The values for the manganese ion complex are $k_o^{Mn} = 4 \times 10^{-4}$ min^{-1} and $k_{OH}^{Mn} = 1.4 \times 10^5$ M^{-1} min^{-1}. The water rate constant is three times larger than that for the uncomplexed species. The hydroxide rate constant is fourteen times larger.

The data for catalysis by pyridine show a small but consistent deviation from the value expected from a Brønsted plot based on other unhindered bases (The Brønsted plot is discussed in the next section). This suggested the possibility that the conjugate acid of pyridine may be catalytic. This was tested by measuring observed rate as a function of buffer ratio. A plot of observed rate against buffer ratio for pyridine catalysis (points at fraction of free base 0.9, 0.4, 0.1) reveals that only the basic component of the buffer is catalytic. Therefore, any deviation is due to the empirical nature of analysis using the Brønsted catalysis law.

According to the mechanism in Scheme I, the observed rate of reaction in the presence of a single added base and metal ion is:

$$v = (k_b[B] + k_o + k_{OH}[OH])[SH^-] + (k_b^m[B] + k_o^m + k_{OH}^m[OH])[SH^-\cdot M] = -dI_2/dT = k_{obsd}[SH^-]_t \quad (1)$$

The known concentration of substrate, both complexed and uncomplexed is $[SH^-]_t$.

$$[SH^-]_t = [SH^-] + [SH^-\cdot M] \quad (2)$$

The equilibrium constants K^m are the association constants for magnesium and manganese ions and the substrate:

$$K^m = [SH^-\cdot M]/([SH^-][M]) \quad (3)$$

The general expression for k_{obsd} then is $v/[SH^-]_t$ with the concentrations of added base and metal ion as well as solution pH being known. In the absence of added metal ion, $[SH^-] = [SH^-]_t$ and observing k_{obsd} with variation of [B] gives the value of k_b as the slope of a plot of k_{obsd} as a function of [B]. The intercept of that plot at [B] = 0 gives the water and hydroxide rate constants as discussed above. At any specified pH and metal ion concentration, we can define:

$$k' = k_o + k_{OH}[OH] \quad (4)$$

$$k'^m = k_o^m + k_{OH}^m[OH] \quad (5)$$

$$k'_t = k'([SH^-]/[SH^-]_t) + k'^m[SH^-\cdot M]/[SH^-]_t \quad (6)$$

The term k'_t is the intercept at zero base concentration of a plot of k_{obsd} as a function of base concentration at any metal concentration.

Equations 1–6 can be combined and rearranged to give an expression that is useful for obtaining the remaining rate constants from observed iodination rates with varying metal ion and base concentrations.

$$k_{obsd} - k'_t = k_b[B](1/(1 + K^m[M])) + k_b^m[B]K^m[M](1/(1 + K^m[M])) \quad (7)$$

We define k'_{obsd}:

$$k_{obsd} - k'_t = k'_{obsd} \quad (8)$$

$$k'_{obsd} = k_b(1/(1 + K^m[M]))[B] + k_b^m K^m[B][M](1/(1 + K^m[M])) \quad (9)$$

Plots following eq 9 were used to obtain values for k_b^m after values for K^m were determined. Since catalysis by the metal ions was observed to show saturation, the values for K^m can be determined by kinetic procedures. Equations for such determinations have been established for other catalytic systems with significant background rates and our resulting equations and plots are similar in form to those that have been reported.[19,20] We define the term Q:

$$Q = (k'_{obsd}/[B]) - k_b \quad (10)$$

By the use of eq 1, 7, and 10:

$$Q = (k_b^m - k_b)(K^m[M])/(1 + K^m[M]) \quad (11)$$

or,

$$1/Q = (1/(k_b^m - k_b)K^m)(1/[M]) + 1/(k_b^m - k_b) \quad (12)$$

The value of K^m is obtained from the x intercept of a plot of $1/Q$ vs $1/[M]$ for each metal, assuming the binding constant of the metal to the substrate is independent of the identity of the uncomplexed base. We used pyridine for all determinations of K^{Mg} and K^{Mn}. The values for each k_b^m were then obtained by substituting the measured parameters into eq 9 It should be noted that a meaningful value of K^m is obtained only if there is observable saturation by the catalyst (that is, a plot of $1/Q$ vs $1/[M]$ must have a significant y intercept). Our results are shown in Figure 1a and 1b. However, since the plot involves a lengthy extrapolation to the intercepts at the axes from data that is subject to considerable uncertainty, the binding constants should be considered to be approximate values. For the same reason, we prefer to fit our experimental data directly by substituting into the equations developed in the text, rather than using values which could be obtained from the y-axis intercepts in Figure 1. These data are summarized in Table I.

Brønsted Plots. To establish the steric effects of the bases in the metal ion catalyzed process, we first determined a Brønsted plot for catalysis by pyridines of varying basicity that do not have a substituent on the carbon atom adjacent to the nitrogen atom (positions 2 or 6). This plot is presented in Figure 2. The rates of enolization due to catalysis by sterically hindered bases (2,6-lutidine, 2,4-lutidine, and 2-picoline) are also shown but were not used to determine the line in the plot. The deviations of the observed rates with these catalysts from the Brønsted plot for the unhindered bases form the basis of our evaluation of the mechanism by which the metal ions enhance the rates of proton transfer.

Discussion

Earlier studies have demonstrated that a divalent metal ion can promote the general base catalyzed enolization of MAcP.[9]

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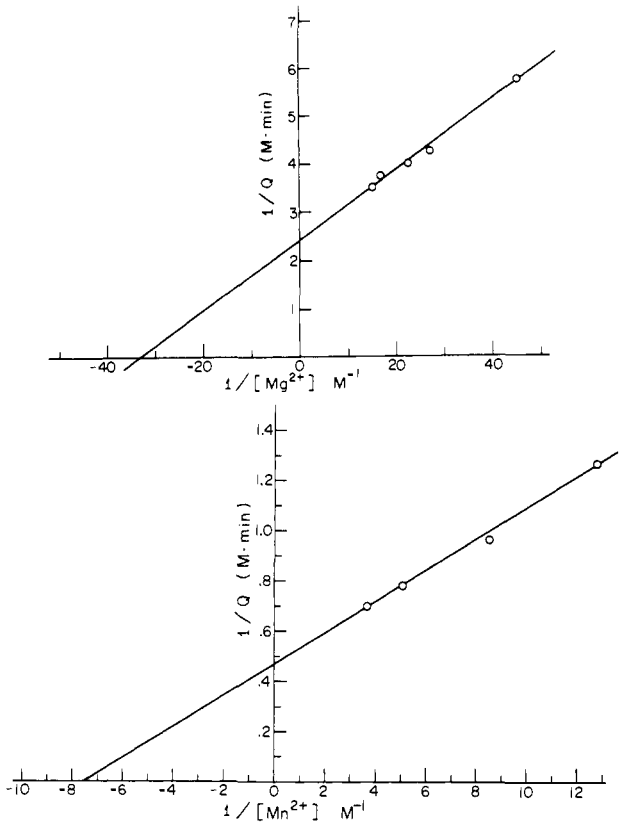

Figure 1. Plots of data for metal ion dependence of observed rate constants for enolization of methyl acetonylphosphonate in the presence of varying concentrations of metal ions according to eq 12. Catalysis of enolization of MAcP (3.3×10^{-4} M) (a) by magnesium ion and pyridine, ionic strength 0.3 (b) by manganese ion and pyridine, ionic strength 1.0. Intercepts on the 1/[M] axis give affinity constants: $K^{Mg} = 33$ M^{-1} and $K^{Mn} = 7.5$ M^{-1}.

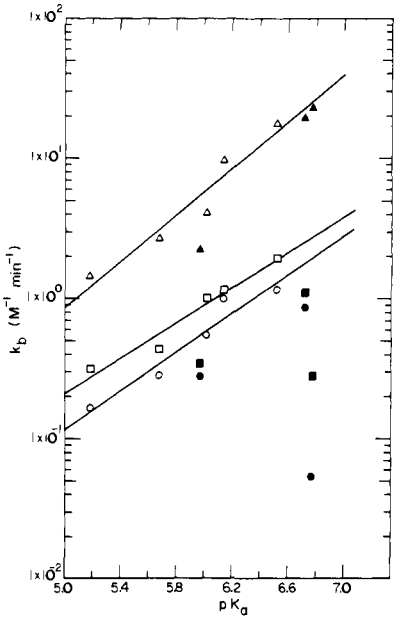

Figure 2. Brønsted plots for the enolization of methyl acetonylphosphonate. The pK_a values correspond to conjugate acids of the bases listed in Table I. The lines have been drawn to give the best fit to data for unhindered bases (open symbols). The "k_b" label refers to values in Table I for k_b (○), k_b^{Mg} (□), and k_b^{Mn} (△). The solid symbols refer to rate constants for catalysis by 2,6-lutidine, 2,4-lutidine, and 2-picoline.

Transfer of a proton from the carbon acid to the pyridine base is an endergonic process and the transition state should resemble the products.[21] Acidification of the substrate by Lewis acid catalysis will make the proton transfer step less endergonic since the coordinated species will be a stronger acid. Coordination of the metal ion to the substrate's carbonyl group should stabilize the developing enolate ion. Steric hindrance will work against the efficacy of catalysis.

Steric effects can be considered in the context of the generally accepted structure of the transition state in the unhindered system. The relationship of the bases and the substrate is normally that which places the proton being transferred in a plane perpendicular to that of the carbonyl functional group. The base is aligned so that the lone pair of electrons on its nitrogen atom is in an orbital that forms a σ bond to the proton being transferred. Therefore, the alignment with the C–H bond should be linear. This proposed structure for the transition state is that which has been presented by Hine and his co-workers and is in accord with the generally accepted orbital picture for transition state stabilization by adjacent π systems.[13] Feather and Gold presented an alternative structure for this transition state in which the amine plane was the *same* as that of the carbonyl group.[11] The nitrogen atom in that model is colinear with the carbonyl functional group. Proton transfer then would occur via a nonlinear transition state without overlap with the adjacent π system. This proposed transition state is much more crowded than is the normally expected one and could account for unusually large steric effects. However, Hine and co-workers argue that the steric effects seen in both their study and that of Feather and Gold can be justified by a molecular mechanics analysis of the normal perpendicular transition state.

The complexes of MAcP with magnesium ion involve primary coordination between the phosphonate functional group and the metal ion.[16] Catalysis of enolization occurs by stabilization of the transition state for proton removal by coordination of the incipient enolate by the metal ion,[2,6] which must involve coordination of the carbonyl group of the substrate. Since this coordination isomer must be present to a very small extent, the rate constant for enolization from this mode must be much larger than the observed rate constant, which is based on the total complex concentration. Although steady state kinetics cannot reveal the rate constant for the active species alone, Cox has shown that in a complex in which the metal is held in place to the carbonyl group of a ketone, the rate of transfer of the adjacent protons to bases is very large compared to uncomplexed species.[6] (Inductive and electrostatic effects on the acidity of the C_1 protons of MAcP resulting from coordination to magnesium ion in these systems are not significant. Dr. Joseph Chan found that the C_3 protons of MAcP are transferred to bases at a much slower rate than the C_1 protons but that the metal ion increases the rate of exchange at both the places by the same factor. Coordination of the carbonyl group to the metal ion therefore must be the principal source of the acceleration since inductive and electrostatic effects from coordination to the phosphonate functional group would be much larger at C_1 than at C_3 [unpublished results quoted in ref 2].)

We have used steric effects due to substituents on the catalytic base as a probe of the transition state of the active catalytic system. Steric effects on rates of proton transfer from MAcP to uncharged bases must be due to changes in transition state structure relative to the structure of the complexed substrate. The structure and relative amount of active complex is independent of the base that will remove the proton in the transition state. Therefore, steric effects serve as a direct probe of structural changes in the transition state.

In the absence of metal ion, the rate constant for enolization of MAcP by 2,6-lutidine is $^1/_{36}$ the value obtained by extrapolation of the Brønsted plot in Figure 2. This indicates the large combined steric effects of methyl groups at the 2 and 6 positions of pyridine on this reaction. For comparison, the rate constant for the monomethylated base, 2-picoline, is only depressed by a factor of $^1/_2$ from the Brønsted line. This depression is not changed in the presence of metal ion. The effect with 2,4-lutidine is also small. Clearly, a single methyl substituent adjacent to the basic site on

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the catalyst will reduce the number of possible modes of entry of the base into the reaction site at the methylene position of MAcP and this may account for the small steric retardation. The metal ion will not affect this statistical effect. However, two methyl substituents in 2,6-lutidine adjacent to the basic site place a much larger limitation than twice the effect of a single methyl group. The additional retardation must be due to a more deep-seated effect on transition state structure. Further data from our study suggest the source of this difference.

The Brønsted plot for the enolization of the magnesium complex of MAcP in the presence of unhindered pyridine bases is shifted upward by almost a factor of two from the line obtained for uncomplexed MAcP but the slope is unchanged within the precision of the data. The rate constants for catalysis by both 2,6-lutidine and by 2-picoline are about 1/10 and 1/2 that expected from the Brønsted plot. The transition state for enolization of the metal complex is such that the steric effect becomes comparable in the two systems. This suggets that the base and MAcP are farther apart in the transition state for reaction of the magnesium complex. Since the reaction of the magnesium complex is faster, extension of the Hammond postulate implies a less endothermic process, making the transition state earlier.[21] This is consistent with the reduced steric effect for the very bulky catalyst but the change in the slope of the Brønsted plot is not significant as would be expected for a changing position in a common transition state.

The Brønsted plot for enolization of the manganese ion complex of MAcP reveals that the complex is more reactive than the uncomplexed species by about a factor of ten. The steric effects on the reaction due to the methyl groups of 2,6-lutidine and 2,4-lutidine are almost nonexistent. That for 2-picoline is about the same as in the case of MAcP and its magnesium complex. The significantly large decrease in steric effect for reactions of the metal complexes with 2,6-lutidine implies that the structure of the transition state in the complexed and uncomplexed cases are very different, while that for 2-picoline remains constant. Since 2-picoline is a weaker base than the disubstituted pyridines, it is possible that the alternative transition state structure is more sensitive to basicity, giving the associated mechanism a higher Brønsted beta value and making it most important for the more basic amines.

The slopes of the Brønsted plots for enolization of the magnesium complex and for uncomplexed MAcP are equal within the uncertainties of the procedures used to determine the plot (0.62 and 0.69, with correlation coefficient of 0.97). The slope of the plot for the manganese complex is larger (0.86, with a correlation coefficient of 0.97). The larger slope for the manganese complex is opposite to expectations from the reactivity–selectivity principle,[21] if only variations in atomic positions within a common transition state occur. A consistent interpretation is possible if we assume that the change in transition state structure involves a substantial change in the relationship between the base catalyst and substrate. This is the same conclusion we draw from the change in steric effects. We propose that the metal complexes have available an alternative mechanism which is most important in the case of the reaction of the manganese complex but contributes to the magnesium complex reaction as well. We can interpret our data based upon one possible alternative transition state structure, with the assumption that in the absence of metal, the structure of the transition state is that proposed by Hine et al.[13]

We suggest that the metal ion may permit catalysis to occur via a coordinated water molecule which forms a bridge between the base and the substrate. Prior to coordination to the substrate, manganous ion and magnesium ion exist as octahedrally coordinated hexahydrates. The substrate substitutes for one water ligand with primary coordination through an oxygen atom of the phosphonate function. The carbonyl group oxygen also can coordinate but to a smaller extent. This bidentate mode of coordination enables the metal ion to function as a Lewis acid catalyst. In addition, an adjacent coordinated water can serve to transfer a proton between the coordinated substrate and the sterically hindered base. The observed buffer catalysis requires that the base be present during the transfer of the proton from the substrate. The coordinated water serves as a relay for the transfer. This process will have a substantially smaller sensitivity to steric effects than a direct transfer. This is followed by a series of rapid steps which release the enolized product that is trapped by iodine.

An illustration of the proposed alternative mechanism for the reaction of the manganese complex of MAcP with 2,6-lutidine is summarized in Scheme II. MAcP is symbolized as SH^- and its conjugate base is S^{2-}. The charge on the metal ion is omitted.

Scheme II

$$Mn(H_2O)_6 + HS^- \rightarrow Mn(HS^-)(H_2O)_4 + 2H_2O$$

$$Mn(HS^-)(H_2O)_4 + B \xrightarrow{\text{slow}} Mn(S^{2-})(H_2O)_4 \cdot BH^+$$

$$Mn(S^{2-})(H_2O)_4 \cdot BH^+ \rightarrow Mn(S^{2-})(H_2O)_4 + BH^+$$

$$Mn(S^{2-})(H_2O)_4 + 2H_2O + H^+ \rightarrow \text{enol} + Mn(H_2O)_6$$

There is precedent for this type of metal ion–substrate bridge mechanism in other catalytic reactions. Such mechanisms have been proposed to occur in enzymic reactions[3,22] and in biomimetic systems.[23,24]

Acknowledgment. We thank Kyong-Soon Lee for her help in carrying out some of the experiments reported here. Support for this research was provided by the Natural Sciences and Engineering Research Council of Canada through an operating grant. Margaret Wong received an Ontario Graduate Scholarship in 1982 and a N.S.E.R.C. Scholarship in 1983.

Registry No. MAcP, 52011-39-9; Mg^{2+}, 22537-22-0; Mn^{2+}, 16397-91-4; sodium methyl acetonylphosphonate, 40463-77-2; pyridine, 110-86-1; 3-picoline, 108-99-6; 2-picoline, 109-06-8; 4-picoline, 108-89-4; 3,5-lutidine, 591-22-0; 3,4-lutidine, 583-58-4; 2,4-lutidine, 108-47-4; 2,6-lutidine, 108-48-5.

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