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Modulation of Tautomeric Equilibria by Ionic Clusters. Acetylacetone in Solutions of Lithium Perchlorate−Diethyl Ether[‡]

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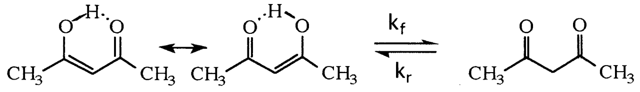
Abstract: Acetylacetone (2,4-pentanedione, **1**) is a molecule whose tautomeric forms are in dynamic equilibrium. Concentrated salt solutions in nonaqueous solvents exert a remarkable influence on the keto−enol ratio of this β-diketone. The keto content of **1** increases from 5% in pure diethyl ether to 84.5% in a 4.14 M lithium perchlorate−diethyl ether (LPDE) solution, a nearly 17-fold increase. The equilibrium expression, $K = [\text{keto}]/[\text{enol}] = k_f/k_r$, exhibits a linear dependence on [$LiClO_4$], with the formal order of participation of lithium ion in the equilibrium being 1.0. A kinetic analysis reveals that k_f is independent of LPDE concentration, whereas k_r displays an inverse dependence on salt concentration, indicating preferential coordination of the keto tautomer with Li^+. Although **1** exits as the enol in water only to the extent of 16%, the addition of lithium perchlorate further reduces this figure. In an aqueous 4.02 M $LiClO_4$ solution, acetylacetone enol accounts for only 4.6% of the total amount of 2,4-pentanedione present. It has also been found that acetylacetone itself is an excellent solvent for $LiClO_4$ as well as for $NaClO_4$ with solutions containing up to 7.5 M $LiClO_4$ attainable. The enol content of **1** decreases dramatically from 81% to 7.4% on going from the neat liquid to a solution of 6.39 M $LiClO_4$ in acetylacetone.

Introduction

Ever since the classic work of Knorr and Meyer on the two forms of acetylacetone, ethyl acetoacetate, and other β-diketones, tautomerization has been the subject of intense interest.[1a−e] Tautomeric equilibria, particularly keto−enol systems, play an important role in many biological processes. In aromatic heterocyclic systems in solution, the keto is the predominate, even exclusive, species at equilibrium, while in the gas phase the situation is reversed.[1f,g] For example, in ethanol 4-pyridone is the only tautomer present but in the gas phase 4-hydroxypyridine is the major form.[1h,i] In contrast to simple carbonyls, β-diones such as acetylacetone, 2,4-pentanedione (**1**), are enolized to such a large extent that both tautomers are present in measurable concentration at equilibrium, Scheme 1.[2]

Scheme 1



1

While the tautomerization of **1** is base catalyzed, it is quite insensitive to catalysis by the hydronium ion.[3a] However, the enolization of **1** is powerfully catalyzed by divalent metal ions.[3b] This tautomeric equilibrium has been shown to be exquisitely sensitive to solvent polarity and hydrogen-bonding capacity. Acetylacetone is ca. 96% enolized in the gas phase, 95% in cyclohexane and diethyl ether, and 62% in acetonitrile, but only 16% in aqueous solution, Table 1.[4] In addition to stabilizing interactions due to solvent polarity, there are strong hydrogen-bonding interactions between the diketo form and water, which are lost on going to the vapor phase or to a nonpolar, hydrophobic solvent system. The enols of most acyclic β-diketones and β-ketoesters exist in the cis enol form where they are

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[†] Current address: Department of Chemistry, Seattle University, Seattle, WA 98122.

(1) (a) Knorr, L. *Ann.* **1896**, *70*, 293. (b) Knorr, L. *Ann.* **1899**, *76*, 322. (c) Meyer, K. H.; Koppelmeier, P. *Ber.* **1911**, *44*, 2718. (d) Meyer, K. H. *Ber.* **1912**, *45*, 2843. (e) Knorr, L.; Rothe, O.; Averbeck, H. *Ber.* **1911**, *44*, 1138. (f) Katritzky, A. R.; Karelson, M.; Harris, P. A. *Heterocycles* **1991**, *32*, 329. (g) Beak, P. *Acc. Chem. Res.* **1977**, *10*, 186. (h) Beak, P.; Fry, F. S., Jr.; Lee, J.; Steele, F. *J. Am. Chem. Soc.* **1976**, *98*, 171. (i) For the use of 2-pyridone as a tautomeric catalyst, see: Rony, P. R. *J. Am. Chem. Soc.* **1969**, *91*, 6090.

(2) (a) For an excellent review of β-diketones and β-thioxo ketones, see: Emsley, J. *J. Struct. Bonding*, **1984**, *57*, 149−190. (b) For an outstanding review on the biochemistry of tautomerization reactions, see: Pollack, R. M.; Bounds, P. L.; Bevins, C. L. In *The Chemistry of Functional Groups*: *Enones*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons: New York, 1989; pp 559−597. For reviews of acetylacetone and other β-diketones in inorganic chemistry, see: (c) Mehrotra, R. C. *Pure Appl. Chem.* **1988**, *60*, 1349. (d) Saito, K.; Jido, H.; Nagasawa, A. *Coord. Chem. Rev.* **1990**, *100*, 427. For recent reviews of simple enols and their generation, see: (e) Kresge, J. *Acc. Chem. Res.* **1990**, *23*, 43. (f) Hart, H. *Chem. Rev.* **1979**, *79*, 515. (g) Toullec, J. *Adv. Phys. Org. Chem.* **1982**, *18*, 1. (h) Capon, B.; Guo, B.-Z.; Kwok, F. C.; Siddhanta, A. K.; Zucco, C. *Acc. Chem. Res.* **1988**, *21*, 135. (i) Rappoport, Z.; Biali, S. E. *Acc. Chem. Res.* **1988**, *23*, 442. For simple enol systems where the enol is the major tautomer present at equilibrium, see: (j) Linder, P. E.; Correa, R. A.; Gino, J.; Lemal, D. M. *J. Am. Chem. Soc.* **1996**, *118*, 2556. (k) Linder, P. E.; Lemal, D. M. *J. Org. Chem.* **1996**, *61*, 5109. (l) Correa, R. A.; Linder, P. E. *J. Am. Chem. Soc.* **1994**, *116*, 10795.

(3) (a) Bell, R. P.; Lidwell, O. M. *Proc. R. Soc.* **1940**, *A176*, 88. (b) Meany, J. E. *J. Phys. Chem.* **1969**, *73*, 3421.

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Table 1. Enol Content of Acetylacetone in Different Solvents and in the Gas Phase[a]

solvent	ϵ^b	percent enol	reference
gas phase	1.0	92, 93, 97.6	4l, 4m, 4k
C_6H_{12}	2.0	91, 96, 97	4g, 4f, 4e
dioxane	2.2	82[c]	4b
CCl_4	2.2	94.6, 95, 95, 96[c]	4j, 4e, 4f, 4b
C_6H_6	2.3	89,[c] 97	4b, 4j
$(CH_3CH_2)O$	4.3	95[c]	4b
$CHCl_3$	4.8	82.6, 87	4j, 4g
CH_3CO_2H	6.2	67,[c] 73, 73.4	4b, 4g, 4j
C_5H_5N	12.3	82	4h
CH_3CH_2OH	24.3	74.4, 82[c]	4j, 4b
neat	25.7	80.9,[c] 81, 82	4a, 4e, 4f
CH_3OH	32.6	68, 74,[c] 74	4j, 4b, 4e
CH_3CN	36.2	52.9, 62[c]	4j, 4b
DMA	37.0	66	4e
$(CH_3)_2SO$	46.6	60,[c] 62, 63	4b, 4e, 4f
H_2O	78.5	15.5,[d] 16	4i, 4e

[a] At 25 °C unless otherwise noted. [b] Taken from: *Handbook of Chemistry and Physics*, 60th ed.; Weast, R. C., Ed.; CRC Press: Boca Raton, FL, 1980; pp E56−E58. [c] At 33 °C. [d] At 20 °C.

stabilized by conjugation and intramolecular hydrogen bonds, Scheme 1.[5] Furthermore, the two Kekule structures that can be depicted for symmetrical acyclic enols such as acetylacetone are equivalent, implying that the hydrogen bond is symmetrical. This has been shown to be the case by electron diffraction studies.[5,6]

Previous work in these laboratories has elaborated on the early observations of Willard et al. and Sillén et al. concerning the extraordinary solubility of strictly anhydrous lithium perchlorate in diethyl ether.[7−18] Solutions containing up to 6.06 M lithium perchlorate in ether, hereafter LPDE, are possible. These highly polar concentrated salt solutions have been shown by conductivity and vapor pressure data to exist as complex ionic clusters composed of $LiClO_4$ and Et_2O, rather than simple aggregates of ions.[8,9] Solubility−temperature curves, NMR spectroscopy, and heats of solution measurements indicate that below 4.25 M LPDE, these solutions are composed of $Li(OEt_2)_2^+\ ClO_4^-$ ions, while above 4.25 M, a mixture of $Li(OEt_2)_2^+\ ClO_4^-$ and $Li(OEt_2)^+\ ClO_4^-$ exists.[10] The limit of solubility, 6.06 M, corresponds to the ionic composition $Li(OEt_2)^+\ ClO_4^-$.

Pocker and Buchholz used the ionization of triphenylmethyl chloride as a sensitive probe of the ionic environment present in these solutions and observed a 7×10^9 fold increase in trityl cation formation on going from pure ether to a 5.0 M LPDE solution.[10] Similarly, the rate of rearrangement of 1-phenylallyl chloride to cinnamyl chloride rises 8.56×10^4 fold on going from ether to 3.39 M LPDE, while the aminolysis of 4-nitrophenyl acetate by imidazole is accelerated by a factor of 5.8×10^4 from 0 to 4.49 M LPDE.[11,13,14] The solvatochromatic behavior of Reichardt's dye, phenol blue, and substituted nitroanilines in these media has been explored as has the ability of these solutions to facilitate proton-transfer reactions.[16−18] Braun and Sauer derived Ω values, and from these approximate E_T30 values, for LPDE solutions by observing the *endo*/*exo* product ratio for the Diels−Alder reaction between cyclopentadiene and methyl acrylate.[19] Forman and Dailey noted a 8.9-fold rate increase for the [4+2] cycloaddition of 9,10-dimethylanthracene and acrylonitrile.[20] Recent work has focused on exploiting the synthetic utility of these media.[21]

We have expanded on our earlier observations by investigating the effects of these room-temperature molten salt solutions

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(4) (a) Burdett, J. L.; Rogers, M. T. *J. Am. Chem. Soc.* **1964**, *86*, 2105. (b) Burdett, J. L.; Rogers, M. T. *Can. J. Chem.* **1965**, *43*, 1516. (c) Burdett, J. L.; Rogers, M. T. *J. Phys. Chem.* **1966**, *70*, 939. (d) Billman, J. H.; Sojka, S. A.; Taylor, P. R. *J. Chem. Soc., Perkins Trans. 2* **1972**, 2034. (e) Spencer, J. N.; Holmboe, E. S.; Kirshenbaum, M. R.; Firth, D. W.; Pinto, P. B. *Can. J. Chem.* **1981**, *60*, 1178. (f) Allen, G.; Dwek, R. A. *J. Chem. Soc. B* **1966**, 161. (g) Reeves, L. W. *Can. J. Chem.* **1957**, *35*, 1351. (h) Kondo, G.; Takemoto, T.; Ikenone, T. *J. Chem. Soc. Jpn. Ind. Chem. Sect.* **1968**, *68*, 1404. (i) Schwarzenbach, G.; Felder, E. *Helv. Chem. Acta* **1944**, *27*, 1044. (j) Emsley, J.; Freeman, N. J. *J. Mol. Struct.* **1987**, *161*, 193. (k) Folkendt, M. M.; Weiss-Lopez, B. E.; Chauvel, J. P., Jr.; True, N. S. *J. Phys. Chem.* **1985**, *89*, 3347. (l) Mella, T. P.; Merrifield, R. *J. Appl. Chem.* **1969**, *19*, 79. (m) Strohmeier, W.; Huhne, I. *Z. Naturforsch.* **1952**, *7B*, 184. For ^{17}O NMR work performed on acetylacetone and other β-diketones, see: (n) Gorodetsky, M.; Luz, Z.; Mazur, Y. *J. Am. Chem. Soc.* **1967**, *89*, 1183. (o) Luz, Z.; Silver, B. *J. Phys. Chem.* **1966**, *70*, 1328.

(5) For the crystal structure of **1**, see: (a) Boese, R.; Antipin, M. Y.; Bläser, D.; Lyssenko, K. A. *J. Phys. Chem. B* **1998**, *102*, 8654. (b) Lowery, A. H.; D'Antonio, P.; George, C.; Karle, *J. Am. Chem. Soc.* **1971**, *93*, 6399. (c) Andreassen, A. L.; Bauer, S. H. *J. Mol. Struct.* **1972**, *12*, 381. For recent quantum mechanical calculations of the enol of **1**, see: (d) Mavri, J.; Grdadolnik, J. *J. Phys. Chem. A* **2001**, *105*, 2045. (e) Mavri, J.; Grdadolnik, J. *J. Phys. Chem. A* **2001**, *105*, 2039.

(6) (a) Camerman, A.; Mastropaolo, D.; Camerman, N. *J. Am. Chem. Soc.* **1983**, *105*, 1584. These authors have published a structure of acetylacetone in the presence of diphenylhydantoin and 9-ethyladenine where the hydrogen bond is not symmetrical. They claim that there are no interactions between the tautomers of acetylacetone and the cosolutes. Crystal structures of other symmetrical β-diketones, such as 1,3-diphenyl-1,3-propanedione, ref 6b, reveal symmetrical enols. An interesting case where an unsymmetrical enol exists is that of 3-phenyl-1-(2,4,6-triphenylphenyl)propane-1,3-dione, ref 6c. Here, steric considerations force the hydroxy group to be in the neighborhood of the unsubstituted phenyl ring, and two different C−O bond lengths are observed. (b) Kaitner, B.; Mestrovic, E. *Acta Crystallogr.* **1993**, *C49*, 1523. (c) Abram, S.; Abram, U.; Zimmermann, T. *Acta Crystallogr.* **1993**, *C50*, 765.

(7) (a) Willard, H. H.; Smith, G. F. *J. Am. Chem. Soc.* **1923**, *45*, 286. (b) Schilt, A. A. *Perchloric Acid and Perchlorates*; G. Fredwick Smith Chemical Co.: Columbus, OH, 1979; pp 32−38. (c) For a treatise on the effects of added salt on organic and organometallic chemistry, see: Loupy, A.; Tchoubar, B. *Salt Effects in Organic and Organometallic Chemistry*; VCH: New York, 1992 (originally published in French under the title *Effects de sels en Chimie organique et organometallique*; Editions Bordas: Paris, 1988). For reviews of the role of electrostatics in biomolecular recognition and control, see: (d) Carbeck, J. D.; Colton, I. J.; Gao, J.; Whitesides, G. M. *Acc. Chem. Res.* **1998**, *31*, 343. (e) Koshland, D. E., Jr. *Pure Appl. Chem.* **1971**, *25*, 119.

(8) Eklelin, K.; Sillén, L. G. *Acta Chem. Scand.* **1953**, *7*, 987.

(9) (a) Johnson, O. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1948. (b) Chu, J. C. H. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1949.

(10) Pocker, Y.; Buchholz, R. F. *J. Am. Chem. Soc.* **1970**, *92*, 2075.

(11) Pocker, Y.; Buchholz, R. F. *J. Am. Chem. Soc.* **1970**, *92*, 4033.

(12) Pocker, Y.; Buchholz, R. F. *J. Am. Chem. Soc.* **1971**, *93*, 2905.

(13) Pocker, Y.; Ellsworth, D. L. *J. Am. Chem. Soc.* **1977**, *99*, 2276.

(14) Pocker, Y.; Ellsworth, D. L. *J. Am. Chem. Soc.* **1977**, *99*, 2284.

(15) Pocker, Y.; Ciula, J. C. *J. Am. Chem. Soc.* **1988**, *110*, 2904.

(16) Pocker, Y.; Ciula, J. C. *J. Am. Chem. Soc.* **1989**, *111*, 4728.

(17) Pocker, Y.; Spyridis, G. T. *J. Am. Chem. Soc.* **2002**, *124*, 7390.

(18) (a) Reuber, M. S.; Pocker, Y. *Proceedings of the 6th International Symposium on Solute−Solute−Solvent Interactions*; Pergamon Press: Oxford, 1982; 5P-13. (b) Rueber, M. S. Ph.D. Thesis, University of Washington, Seattle, WA, 1987.

(19) Braun, R.; Sauer, J. *Chem. Ber.* **1986**, *119*, 1269.

(20) Forman, M. A.; Dailey, W. P. *J. Am. Chem. Soc.* **1991**, *113*, 2761.

(21) For the synthetic utility of the solvent system lithium perchlorate−diethyl ether, see: (a) Heydari, A.; Larijani, H.; Emami, J.; Karami, B. *Tetrahedron Lett.* **2000**, *41*, 2471. (b) Saito, N.; Grieco, P. A. *Yuki Gosei Kagaku Kyokaishi* **2000**, *58*, 39. (c) Babu, B. S.; Balasubramanian, K. K. *Carbohydr. Lett.* **1999**, *3*, 339. (d) Sankararaman, S.; Nesakumar, J. E. *J. Chem. Soc., Perkin Trans. 1* **1999**, *21*, 3173. (e) Earle, M. J.; McCormac, P. B.; Seddon, K. R. *Green Chem.* **1999**, *1*, 23. (f) Babu, B. S.; Balasubramanian, K. K. *Tetrahedron Lett.* **1998**, *39*, 9287. (g) Kawamura, M.; Kobayashi, S. *Tetrahedron Lett.* **1999**, *40*, 2471. (h) Palani, N.; Chadha, A.; Balasubramanian, K. K. *J. Org. Chem.* **1998**, *63*, 5318. (i) Zarghi, A.; Naimi-Jamal, M. R.; Webb, S. A.; Balalaie, S.; Saidi, M. R.; Ipaktschi, J. *Eur. J. Org. Chem.* **1998**, 197. (j) Jenner, G.; Ben Salem, R. *Tetrahedron* **1997**, *53*, 4637. (k) Kiselev, V. D.; Kashaeva, E. A.; Luzanova, N. A.; Konovalov, A. I. *Russ. J. Gen. Chem.* **1997**, *67*, 1361. (l) Sudha, R.; Maloia, N. K.; Geetha, S. V.; Sankararaman, S. *J. Org. Chem.* **1996**, *61*, 1877. (m) Ipaktschi, J.; Eckert, T. *Chem. Ber.* **1995**, *128*, 1171. (n) Flohr, A.; Waldmann, H. *J. Prakt. Chem.* **1995**, *37*, 609. (o) Wustrow, D. J.; Smith, W. J., III; Wise, L. D. *Tetrahedron Lett.* **1994**, *35*, 61. (p) Ipaktschi, J.; Heydari, A. *Chem. Ber.* **1993**, *126*, 1905. (q) Grieco, P. A. In *Organic Chemistry: Its Language and Its State of the Art*; Kisakurek, M. V., Ed.; VCH: Weinheim, 1993; p 133. (r) Ipaktschi, J.; Heydari, A. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 313. (s) Grieco, P. A. *Aldrichimica Acta* **1991**, *24*, 59. (t) Waldmann, H. *Angew. Chem., Int. Ed. Engl.* **1991**, *24*, 59.

on the keto−enol equilibrium of acetylacetone in various LPDE solutions. We also carried out parallel studies with **1** in aqueous salt solutions to ascertain if the extent of enolization can be further reduced solely by an increase in solvent polarity even in an extremely polar, hydrogen-bonding medium. The forward and reverse rates of equilibration have been determined in an attempt to provide a more complete analysis of the modulation of tautomeric equilibria by such ionic clusters. The systems chosen were solutions of $LiClO_4$ in ether, water, and acetylacetone itself, where solutions up to ca. 7.5 M can be prepared. In addition, sodium perchlorate was found to dissolve in acetylacetone to the extent of ca. 1.7 M.

Experimental Section

General Methods. Kinetic runs were carried out on a Cary 210 spectrophotometer interfaced to an Apple *II*e computer through a bidirectional parallel interface. The cell compartment was maintained at 25.0 ± 0.1 °C with a Forma-Temp Junior model 2095-2 constant-temperature bath. Proton NMR spectra were recorded with a Varian T-60 60 MHz instrument, using TMS as an internal standard, with the sample well set at 33.0 ± 1.0 °C. Infrared spectra were taken on a Perkin-Elmer PE-528 using NaCl plates and solution cells (Aldrich, 0.2083 mm path length).

Anhydrous lithium perchlorate and sodium perchlorate (GFS Chemicals) were recrystallized twice from water and dried at 152 °C under vacuum for at least 24 h. The anhydrous salts were stored under nitrogen or argon in a tightly sealed flask in a desiccator over P_2O_5. Diethyl ether was distilled under dry nitrogen or argon from excess lithium aluminum hydride (Aldrich) just prior to use. Dioxane (Alfa) was distilled under dry nitrogen from sodium and benzophenone. Acetylacetone (Aldrich) was distilled through a jacketed, 50 cm vigreux column (bp = 134 °C at 760 Torr) immediately before use and found to be 99.7% pure via gas chromatography (GC) analysis. Its ^{1}H NMR (neat) spectrum possesses the following resonances: δ 1.98 (s, 3H keto methyl), δ 2.14 (s, 3H enol vinyl methyl), δ 3.57 (s, 2H, keto methylene), δ 5.54 (s, 1H enol vinyl), δ 16.52 (s, 1H enol hydroxy).

Lithium acetylacetonate was prepared by titrating **1** with methyllithium (Aldrich, 1.0 M in ether) in dry ether under nitrogen or argon and stored under nitrogen at −20 °C. Lithium acetylacetonate possesses a λ_{max} of 292 nm and an $\epsilon = 39\,800$ M^{-1} cm^{-1} over the concentration range 0.5−4.0 M LPDE. Its infrared spectrum, taken as a Nujol mull, showed a $\nu_{C=O} = 1610$ cm^{-1} as well as a $\nu_{C=C} = 1520$ cm^{-1}. Although the lithium salt of acetylacetone is insoluble in ether, it is quite soluble in all of the LPDE solutions investigated.

Kinetic Measurements in Ethereal and Aqueous Salt Solutions. Kinetic runs were initiated by injecting 10.0 μL of a 1.2×10^{-2} M acetylacetone−ether solution into 3.0 mL of LPDE solution and monitoring the decrease in absorbance over time at 275 nm. Since 3,3-dimethyl-2,4-pentanedione exists exclusively as the diketone, with a $\lambda_{max} = 310$ nm and an $\epsilon^{310nm} = 170$ M^{-1} cm^{-1} in ether and ethanol, the absorbance observed for acetylacetone at 275 nm is due solely to its enol form.[22] The decrease in absorbance over time is the result of a decrease in enol concentration as the equilibrium shifts to accommodate a medium of greater polarity, Scheme 1. As illustrated in Figure 1, plots of $\ln(A_t - A_\infty)$ versus time reveal that the tautomerization of acetylacetone obeys good first-order kinetics with respect to the β-diketone.

Since tautomerization is a reversible process, the observed rate constant, k_{obsd}, refers to the sum of the first-order constants for the forward, k_f, and reverse, k_r, processes; Scheme 1, eq 1.

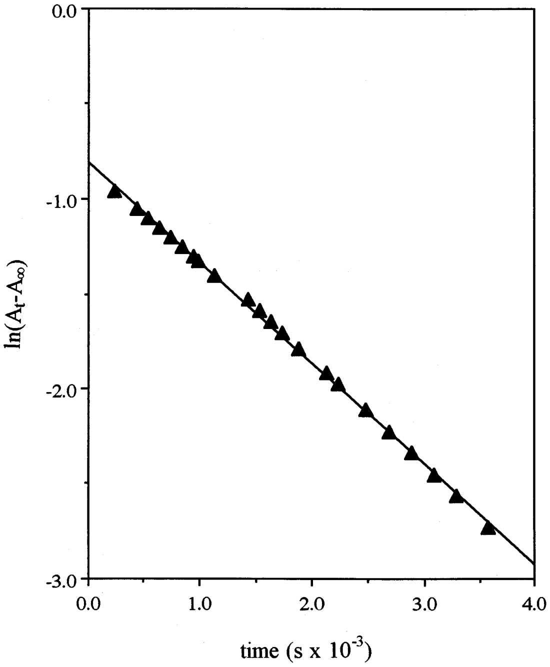

Figure 1. Plot of $\ln(A_t - A_\infty)$ vs time for the re-equilibration of acetylacetone in 4.14 M $LiClO_4-Et_2O$ at 25.0 °C. Here $\ln(A_t - A_\infty) = -0.804 - 0.530t$ ($r = 0.999$).

$$k_{obsd} = k_f + k_r \qquad (1)$$

From the above discussion, Beer's law for this system can be expressed as

$$A = \epsilon_{enol}X_{enol}[\text{acetylacetone}]_{total} = \epsilon_{enol}[\text{enol}] \qquad (2)$$

where X_{enol} is the mole fraction of enol present and ϵ_{enol} is the extinction coefficient of acetylacetone enol. From the A_0 values obtained from the first-order plots and the fact that acetylacetone is 95% enolized in ether, ϵ_{enol} can be expressed as shown in eq 3.

$$\epsilon_{enol} = A_0/(0.95[\text{acetylacetone}]_{total}) \qquad (3)$$

By use of these extinction coefficients as well as the A_∞ values obtained from the trace of absorbance versus time, equilibrium constants, K, for the ketonization of **1** (Scheme 1) can be calculated from eq 4:

$$K = [\text{keto}]/[\text{enol}] = \{[\text{acetylacetone}]_{total} - Q\}/Q = k_f/k_r \qquad (4)$$

where $Q = A_\infty/\epsilon_{enol}$. Table 2 lists k_{obsd}, k_f, and k_r for the ketonization of acetylacetone in various LPDE solutions, while Table 3 lists values of K and the percent enol, P_e, for the tautomerization of acetylacetone in various LPDE solutions. Kinetic runs for a given salt concentration were done at least in triplicate, and ϵ_{enol}, k_{obsd}, and K values were within ±5%.

For aqueous solutions, a similar method was used: 10.0 μL of a 1.5×10^{-2} M acetylacetone−dioxane solution was injected into various $LiClO_4$–H_2O solutions, using 0.82 as the mole fraction of acetylacetone enol present in dioxane.[4b] Table 4 lists values of K, P_e, k_{obsd}, k_f, and k_r for the ketonization of acetylacetone in various aqueous $LiClO_4$ solutions.

Lithium and Sodium Perchlorate−Acetylacetone Solutions. During the course of this investigation, it was found that 2,4-pentanedione can solubilize large quantities of alkali metal perchlorates. For $LiClO_4$−acetylacetone, saturation occurs at a 1:1 solute/solvent mole

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[22] Yoffe, S. T.; Popov, E. M.; Yatsuro, K. V.; Tulikova, E. M.; Kabachnik, M. I. *Tetrahedron* **1962**, *18*, 923.

Table 2. Values of k_{obsd}, k_f, and k_r for the Ketonization of Acetylacetone in Various $LiClO_4-Et_2O$ Solutions at 25.0 °C

[LPDE] (M)	k_{obsd} (min^{-1})	k_f (min^{-1})	k_r (min^{-1})
0.00[a]	2.296	10.6×10^{-2}	2.190
0.056	1.04	7.07×10^{-2}	9.68×10^{-1}
0.10	3.76×10^{-1}	3.42×10^{-2}	3.42×10^{-1}
0.20	1.17×10^{-1}	1.90×10^{-2}	9.75×10^{-2}
0.50	7.37×10^{-2}	2.11×10^{-2}	5.26×10^{-2}
1.00	4.00×10^{-2}	1.83×10^{-2}	2.17×10^{-2}
2.00	3.20×10^{-2}	1.86×10^{-2}	1.35×10^{-2}
3.00	2.66×10^{-2}	1.75×10^{-2}	9.17×10^{-3}
4.14	3.16×10^{-2}	2.42×10^{-2}	7.35×10^{-3}

[a] The solution contained 0.33% methanol.

Table 3. Equilibrium Constants and the Percentage of Enol Form of Acetylacetone Present at Equilibrium for the Tautomerization of Acetylacetone in $LiClO_4-Et_2O$ Solutions at 25.0 °C

[LPDE] (M)	K[a]	P_e[a]
0.00[b]	5.26×10^{-2}	95.0
0.00[c,d]	4.82×10^{-2}	95.4
0.056	0.116	89.6
0.086	0.105	90.5
0.100	0.101	90.9
0.139	0.136	88.0
0.200	0.196	83.7
0.305	0.261	79.3
0.500	0.397	71.6
0.808	0.419	70.5
1.00	0.729	57.8
2.00	1.24	44.6
3.00	1.91	34.4
4.14	3.30	23.3

[a] $K = [\text{keto}]/[\text{enol}]$, with $P_e = 100/(K + 1)$. [b] Taken from ref 4b. [c] This work. [d] The solution contained 0.33% methanol.

ratio (7.52 M), while for $NaClO_4$–acetylacetone solutions, saturation occurs at a solute/solvent mole ratio of 0.2:1.0 (1.73 M).

Since the rate of keto to enol conversion is slow with respect to the NMR time scale, the individual proton and carbon resonances of each tautomer are observed. Burdett and Rogers used the proton resonances to calculate the percentage of enol present in various solvents as well as in neat solutions of various β-diketones and β-ketoesters.[4a−c] Billman et al. utilized the carbonyl resonances in the ^{13}C NMR spectrum and obtained equilibrium constants in good agreement with those obtained via ^{1}H NMR.[4d] The method of Burdett and Rogers was used to calculate the keto−enol ratio at equilibrium for solutions of lithium perchlorate and sodium perchlorate in acetylacetone, using eq 5.

$$K = [\text{keto}]/[\text{enol}] = (\text{area of keto methylene})/2(\text{area of enol vinyl}) \tag{5}$$

For a given salt concentration, the keto methylene and enol vinyl peaks were integrated at least four times and values of K were within ±5%. Table 5 lists values of K and P_e for various $LiClO_4$–acetylacetone and $NaClO_4$–acetylacetone solutions.

Results and Discussion

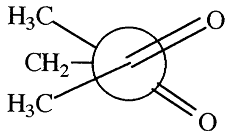
Solutions of Lithium Perchlorate in Diethyl Ether and Water. The addition of perchlorate salts to both nonpolar aprotic and polar protic solvents can drastically alter the keto−enol ratio present in acetylacetone. As outlined in Table 2 for acetylacetone in LPDE solutions, the percentage of enol present at equilibrium decreases from 95.4% in pure ether to 23.2% in 4.14 M LPDE, producing a 66-fold increase in the equilibrium constant. As can be seen in Figure 2, a plot of K versus $[LiClO_4]$ is linear well past 3.0 M LPDE with a slope of 0.69. From Figure 2, $K = 1.0$ and thus [keto] = [enol] at equilibrium occurs at ca. 1.5 M LPDE, which is well within the dietherate region of LPDE. To better understand the dependence of the keto−enol equilibrium of acetylacetone on lithium perchlorate, the minimum order of participation of Li$^+$, n, can be determined as described in eqs 6 and 7

$$K = ([\text{keto}]/[\text{enol}])[LiClO_4]^n \tag{6}$$

$$\ln K = n \ln[LiClO_4] + \ln K' \tag{7}$$

where $K' = [\text{keto}]/[\text{enol}]$ in diethyl ether. From Figure 3, it can be seen that a plot of $\ln(K - K')$ versus ln[LPDE] displays a slope of 0.96 throughout the entire LPDE concentration range investigated, a value extremely close to unity.

From the crystal structure of the diketo form of acetylacetone, the carbonyl groups form a dihedral angle of 48.6°, with an O−O distance of 2.77 Å, **2**.[5b,5c] The main factor which determines the conformation of the keto form of β-dicarbonyls is the strong repulsion of the localized C=O bond dipoles, and such conformations as depicted by **2** account for the large dipole moments of β-dicarbonyls: 3.62 D for 2,4-pentanedione and 3.39 D for ethyl acetoacetate.[23] As lithium ion is known to be tetrahedral in solution with a diameter of 1.56 Å, **3** is envisioned for the interaction of $LiClO_4$–Et_2O clusters with the keto tautomer of acetylacetone in the dietherate region of LPDE.[16,18] Further intimate reactions with ions or ion pairs is not required, and any additional stabilization is due to an increase in the Coulombic forces present in solution upon addition of salt.



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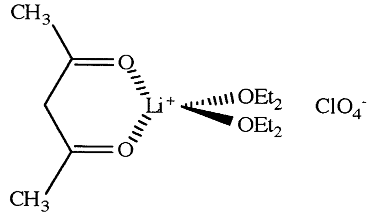

3

Further evidence for the formation of **3** in LPDE solutions is obtained from an analysis of k_f and k_r, Table 2. As the LPDE concentration increases, the rate of re-equilibration decreases; there is a 73-fold rise in the half-life of the reaction on going from pure ether to 4.14 M LPDE. The ratio of ketonization rate constants $k_f^{\text{ether}}/k_f^{4.14\text{M LPDE}} = 4.38$, while $k_r^{\text{ether}}/k_r^{4.14\text{M LPDE}} = 298$. Thus, the rate of diketo formation, enol to keto, is relatively unaffected by salt, while the rate of enolization, keto to enol, shows a marked decrease. From Figure 4, it can be seen that the rate coefficient for the ketonization process displays an inverse dependence on LPDE concentration up to

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(23) (a) Bouma, W. J.; Radom, L. *Aust. J. Chem.* **1978**, *31*, 1649. (b) Naoum, M. M.; Botros, M. G. *Indian J. Chem., Sect A* **1986**, *25*, 427. (c) Emsley, J.; Freeman, N. J.; Parker, R. J.; Overill, R. E. *J. Chem. Soc., Perkin Trans. 2* **1986**, 1489. (d) Naoum, M. M.; Botros, M. G.; Abdel Moteleb, M. M. *Indian J. Chem., Sect A* **1986**, *25*, 639.

Table 4. Equilibrium Constants, the Percentage of Acetylacetone Enol Present at Equilibrium, k_{obsd}, k_f, and k_r for the Ketonization of Acetylacetone in $LiClO_4-H_2O$ Solutions at 25.0 °C[a]

$[LiClO_4]$ (M)	K[a]	P_e[a]	k_{obsd} (s^{-1})	k_f (s^{-1})	k_r (s^{-1})
1.01×10^{-2}	6.97	12.5	9.61×10^{-2}	8.40×10^{-2}	1.21×10^{-2}
5.36×10^{-2}	6.96	12.6	1.08×10^{-1}	9.42×10^{-2}	1.35×10^{-2}
1.79×10^{-1}	7.72	11.5	1.13×10^{-1}	1.00×10^{-1}	1.30×10^{-2}
3.57×10^{-1}	7.07	12.4	1.12×10^{-1}	9.77×10^{-2}	1.38×10^{-2}
1.61	9.49	9.5	1.24×10^{-1}	1.12×10^{-1}	1.12×10^{-2}
3.30	11.3	8.1	1.34×10^{-1}	1.23×10^{-1}	1.10×10^{-2}
4.03	20.7	4.6	1.78×10^{-1}	1.70×10^{-1}	8.00×10^{-3}

[a] K = [keto]/[enol], with $P_e = 100/(K + 1)$.

Table 5. Equilibrium Constants and the Percentage of Acetylacetone Enol Present at Equilibrium for the Tautomerization of Acetylacetone in $LiClO_4$–Acetylacetone and $NaClO_4$–Acetylacetone Solutions at 33.0 °C

$[MClO_4]$ (M)	K[a]	P_e[a]
0.00[b]	0.236	80.9
0.00[c]	0.235	81.0
0.00[d]	0.220	82.0
0.00[e]	0.231	81.2
0.200[f]	0.306	76.5
0.562[f]	0.278	78.2
0.816[f]	0.398	71.5
0.944[f]	0.431	69.8
1.71[f]	0.646	60.7
2.31[f]	1.07	48.3
3.90[f]	2.27	30.5
5.05[f]	4.07	19.7
6.39[f]	12.4	7.4
0.362[g]	0.332	75.1
0.814[g]	0.429	69.9
1.13[g]	0.500	66.7
1.46[g]	0.577	63.4
1.61[g]	0.836	54.5

[a] K = [keto]/[enol], with $P_e = 100/(K + 1)$. [b] Taken from ref 4a. [c] Taken from ref 4e. [d] Taken from ref 4f. [e] This work. [f] $LiClO_4$–acetylacetone solutions. [g] $NaClO_4$–acetylacetone solutions.

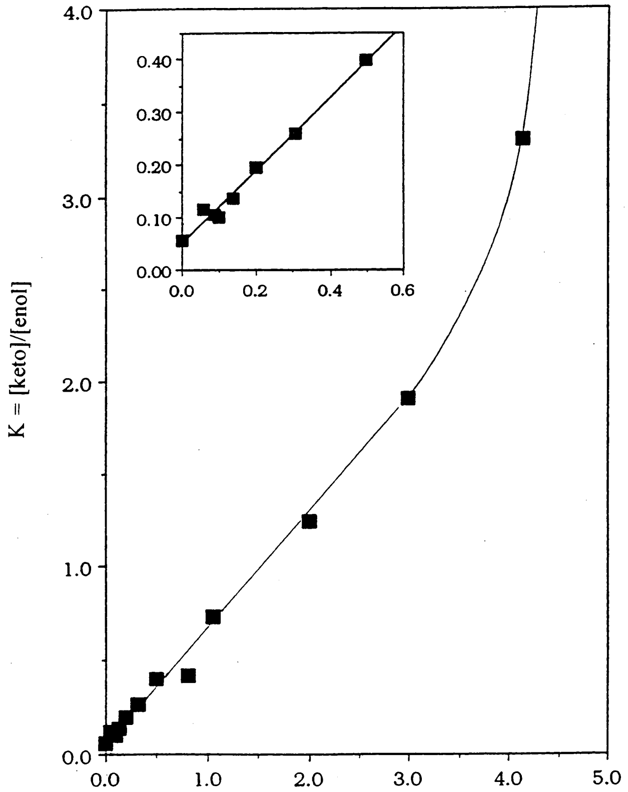

Figure 2. Plot of K = [keto]/[enol] vs $[LiClO_4]$ for the ketonization of acetylacetone in the solvent system $LiClO_4-Et_2O$. The equation for the linear portion of the curve is $K = 0.687[LiClO_4] + 5.23 \times 10^{-2}$ ($r = 0.997$). The inset shows the relationship between K and [LPDE] over the range 0.0–0.6 M LPDE.

ca. 0.2 M and then becomes independent of added salt, while the rate coefficient for the enolization reaction exhibits an inverse dependence on LPDE concentration throughout the entire range of salt concentration. Thus, stabilization of the keto tautomer, as in **3**, reduces the rate of enolization but leaves the velocity of ketonization untouched, resulting in a decrease in the overall reaction rate as the salt concentration is increased.

Previous investigations concerning the effect of lithium perchlorate on the reaction rates and positions of equilibria of various reactions all showed increases in the formal order of participation of lithium perchlorate as the [LPDE] increased. For the ionization of trityl chloride and the acid–base reaction of HCl with pyridine in LPDE, *n* increased steadily from 2 to 12.[10] For the first-order rate constant for the rearrangement of 1-phenylallyl chloride to cinnamyl chloride, *n* grew from 1 to 4 in several $LiClO_4$–solvent mixtures as more salt was added.[13] Similar increases in *n* were observed in the rate constant for the reaction of 4-nitrophenyl acetate with imidazole in LPDE and the acid–base equilibrium between nitrophenols and aromatic amines.[14,18b] However, for the proton-transfer reaction between 2-nitrophenol and imidazole from 0.0 to 3.53 M LPDE, the formal order of participation of $LiClO_4$ remained close to unity until ca. 3 M $LiClO_4$, at which time it began to approach 2.[18b] Pocker and Ciula reported a similar phenomenon for the deprotonation of tropolone by pyridine bases in LPDE; the order in salt increases from 1 to 2.[16] In these cases, a tertiary amine is reacting with an intramolecularly hydrogen-bonded acid, and it is possible to think of the lithium ion as replacing the proton in the hydrogen bond upon deprotonation.

In pure ether, where 95% of the acetylacetone present exists as the enol, the infrared spectrum of **1** is dominated by the conjugated ν_{CCO} stretch centered around 1620 cm^{-1}.[4j,24] As the LPDE concentration is increased, the bands corresponding to the symmetric and asymmetric ν_{CO} stretching modes of the keto tautomer centered around 1730 cm^{-1} increase in intensity due to the increase in diketo concentration. As the salt concentration increases, the symmetric and asymmetric stretching frequencies of the keto carbonyls remain constant. At 0.2 M LPDE, the ν_{CCO} of the enol begins to split into two peaks, one still at 1620 cm^{-1} and another at 1590 cm^{-1}, a phenomenon that becomes more pronounced as the LPDE concentration increases. This

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(24) (a) Fevre, R. J. W.; Welsh, H. *J. Chem. Soc.* **1949**, 2230. (b) Shigorin, D. N. *Zh. Fiz. Khim.* **1950**, *24*, 924.

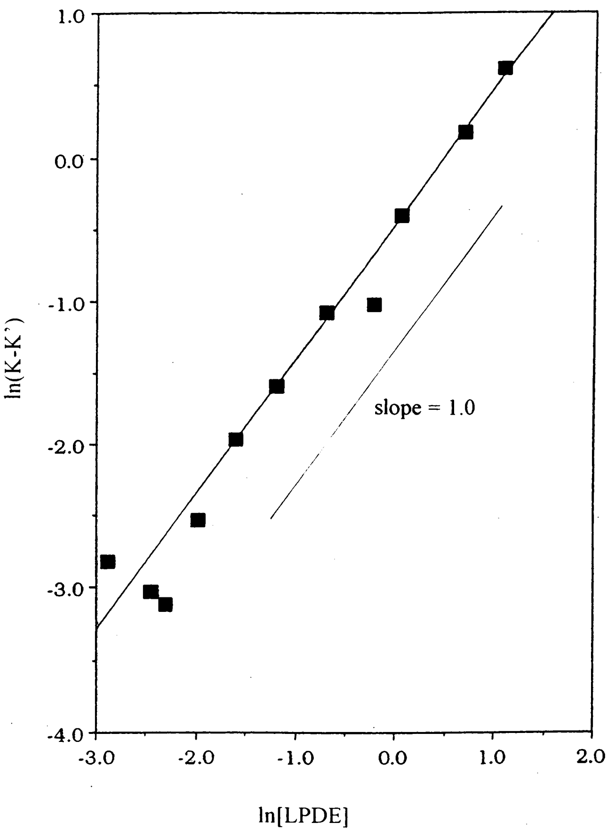
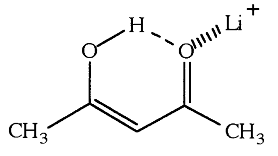


Figure 3. Plot of ln($K_{\mathrm{LPDE}} - K_{\mathrm{ether}}$) vs ln[LiClO$_4$] for the ketonization of acetylacetone in the solvent system LiClO$_4$–Et$_2$O at 25.0 °C. The equation for the line is ln($K - K'$) = −0.524 + 0.96 ln[LiClO$_4$] (r = 0.984).

observation is indicative of the interaction between lithium ion and the enol tautomer as in **4**.



4

This interaction is not as strong as that between Li$^+$ and the keto form of acetylacetone, as the velocity of enol disappearance, k_f, is only slightly reduced by added perchlorate. There is no evidence of enolate ion formation as indicated by a lack of a ν_{CC} at 1520 cm^{-1}. Thus, the addition of LiClO$_4$ to ether dramatically reduces the enol content of acetylacetone by increasing the dielectric constant of the medium, which favors the more polar keto form, as well as by complexing with the diketo tautomer to a much larger extent than with the enol form.

In aqueous solution, the addition of LiClO$_4$ further reduces the already small amount of acetylacetone enol present, Table 4. In pure water, acetylacetone is 16% enolized, while in an aqueous 4.03 M LiClO$_4$ solution that number falls to 4.6%, a 3.5-fold decrease which results in a 3.9-fold increase in the equilibrium constant. As can be seen in Figure 5, a plot of ln($K - K'$) versus ln[LiClO$_4$] shows no dependence on lithium perchlorate until ca. 1 M LiClO$_4$, after which the order of salt participation approaches unity. At low salt concentrations, water itself acts to stabilize the keto tautomer of 2,4-pentanedione via hydrogen bonding, while the enol form can produce its own intramolecular hydrogen bond, Scheme 1, as well as form hydrogen bonds with H$_2$O. Therefore, interactions between lithium ion and the keto form, as in **3**, are not required for stabilization.[4e,4i,25] The observed rate constant, k_{obsd}, exhibits a slight increase with added salt until 3.3 M salt and then begins to increase rapidly, with the percentage of k_{obsd} coming from the rate of ketonization, k_f, rising from 87.4% to 95.5%. A plot of ln k versus ln[LiClO$_4$] shows no dependence on lithium ion for the keto−enol equilibrium until ca. 3 M salt, at which time the forward rate, ketonization, displays a linear dependence on Li$^+$, while the reverse rate, enolization, exhibits an inverse dependence. Due to the hydrogen-bonding capacity and high polarity of water, large amounts of added salt are required in order to observe substantial changes in the enol content of acetylacetone.

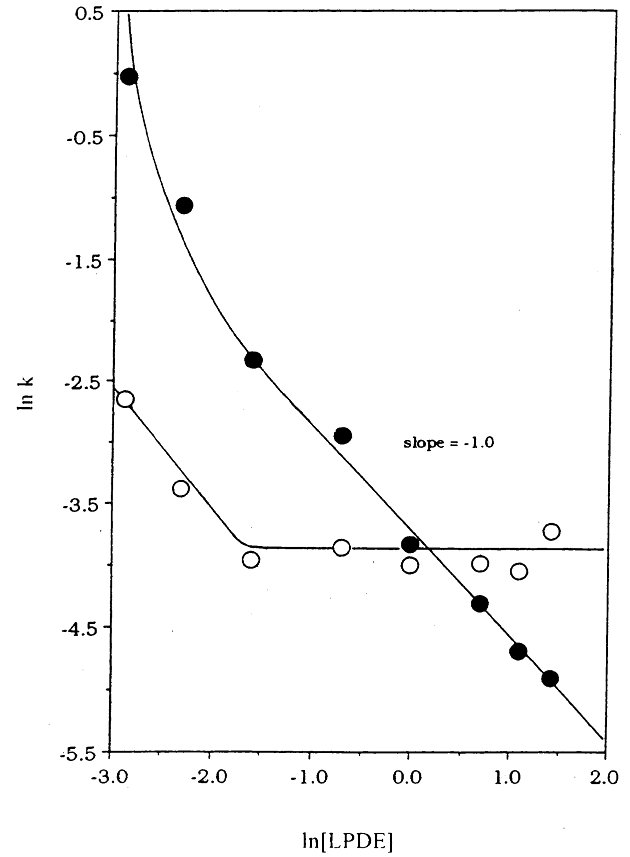


Figure 4. Plot of ln k_f (○) and ln k_r (●) vs ln[LiClO$_4$] for the ketonization of acetylacetone in the solvent system LiClO$_4$−Et$_2$O at 25.0 °C.

Lithium and Sodium Perchlorate Solutions in Acetylacetone. Anhydrous lithium perchlorate is quite soluble in neat acetylacetone (7.52 M), while NaClO$_4$ is much less so (1.73 M). As listed in Table 5, the percentage of enol present at equilibrium decreases from 81% in neat acetylacetone to 54.5% in a 1.61 M sodium perchlorate−acetylacetone solution and 7.4% in a 6.39 M lithium perchlorate−acetylacetone solution, the largest change observed in any of the solvent systems investigated. This corresponds to a 52.5-fold increase in K for mixtures of LiClO$_4$–acetylacetone and a 3.5-fold increase for NaClO$_4$–acetylacetone solutions. Thus, at the solubility limit

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(25) Toulllec, J. In *The Chemistry of Functional Groups*: *The Chemistry of Enols*; Rappoport, Z., Ed.; John Wiley & Sons: New York, 1990; pp 324−398.

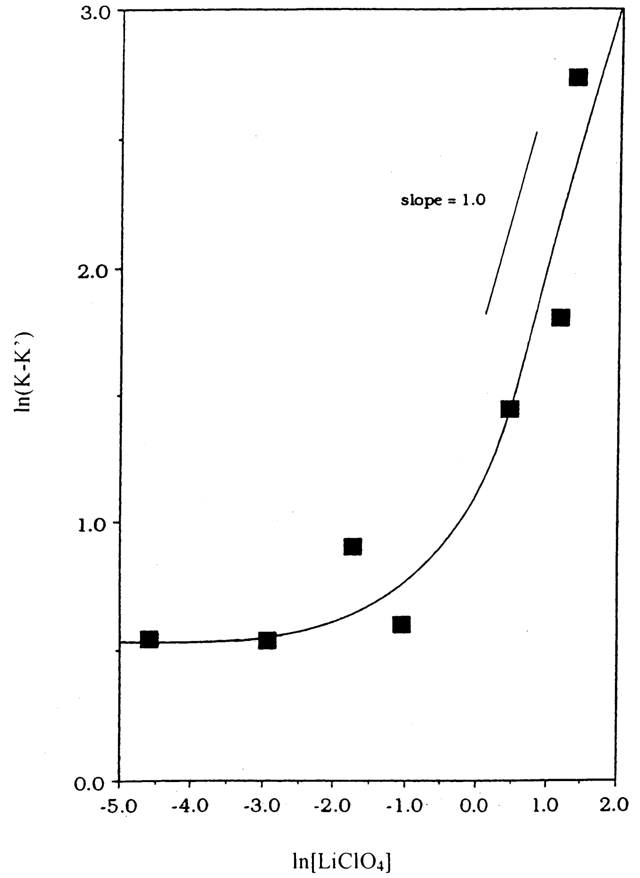


Figure 5. Plot of $\ln(K_{\text{lithium perchlorate-water}} - K_{\text{water}})$ vs $\ln[LiClO_4]$ for the ketonization of acetylacetone in the solvent system $LiClO_4$–H_2O at 25.0 °C.

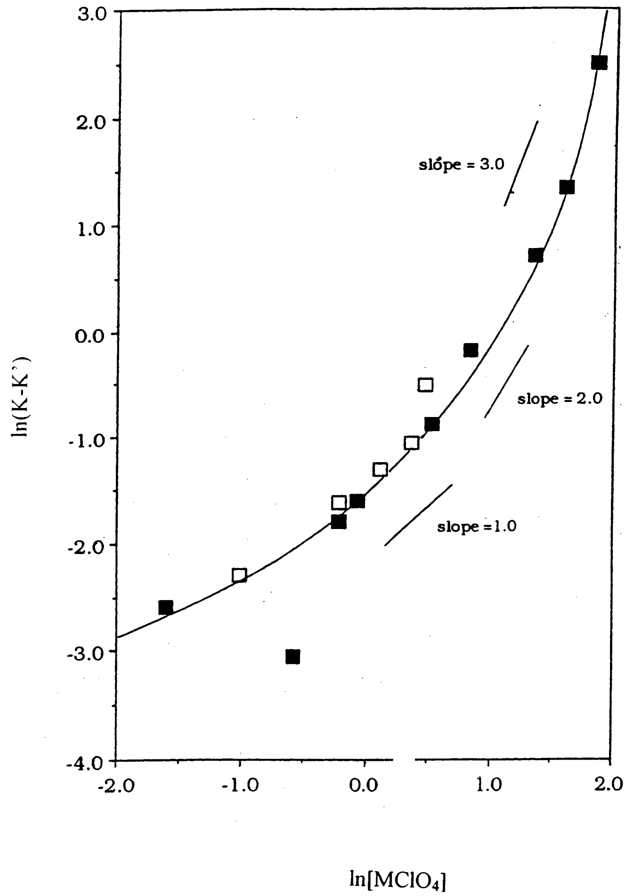
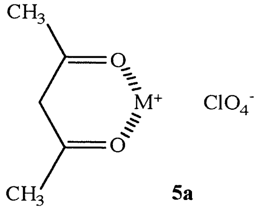
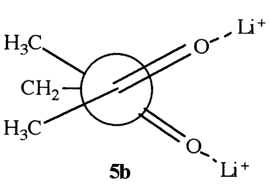


Figure 6. Plot of $\ln(K_{\text{lithium perchlorate-acetylacetone}} - K_{\text{acetylacetone}})$ vs $\ln[MClO_4]$ for the ketonization of acetylacetone in the solvent systems $LiClO_4$–acetylacetone (■) and $NaClO_4$–acetylacetone (□) at 33.0 °C.

of lithium perchlorate in 2,4-pentanedione, the mixture is composed almost entirely of a single tautomeric form of acetylacetone. At ca. 2.3 M $LiClO_4$-acetylacetone, [keto] = [enol] at equilibrium, producing $K = 1.0$. As can be seen in Figure 6, a plot of $\ln(K - K')$ versus $\ln[MClO_4]$ (M = Li or Na) is curved upward, indicating that as the concentration of perchlorate salt is increased, the order of participation of $MClO_4$ with respect to the keto–enol equilibrium of acetylacetone increases as well and that $LiClO_4$ and $NaClO_4$ behave similarly in acetylacetone. For $LiClO_4$-acetylacetone solutions, n approaches unity between 0.0 and 1.6 M salt and then rises to 2 up until 5 M $LiClO_4$. Past 5 M $LiClO_4$, slopes of 3 and higher are observed. For $NaClO_4$-acetylacetone mixtures, the order of participation reaches a maximum value of 1. In the region where $n = 1$, complexes such as **5a**, analogous to **3**, are envisioned. For $n = 2$, where two lithium ions are interacting with a single molecule of diketo, complexes such as **5b** are possible, with larger aggregates observed past 5 M $LiClO_4$.



5a



5b

As the keto form becomes the dominant tautomer, its ν_{CO} stretching modes increase in intensity. When the [2,4-pentanedione]/[$LiClO_4$] ratio approaches 1:1, the enol carbonyl band splits into two peaks, indicative of lithium ion–enol interaction, such as shown by **4**, similar to the behavior observed in LPDE solutions.

Conclusions. The addition of lithium perchlorate to an aprotic solvent of low polarity such as diethyl ether has a dramatic effect on the position of the keto–enol equilibrium of 2,4-pentanedione in these media. As more salt is added, an increase in the polarity of the medium in conjunction with one-to-one coordination of the diketo form by lithium ion drives the position of equilibrium away from the intramolecularly hydrogen-bonded enol toward the more polar keto tautomer. The enol-to-keto rate constant is unaffected by salt, while the rate of enolization, keto-to-enol, decreases. Such stabilization can supplement the hydrogen-bonding capacity present in hydroxylic solvents such as water, where the addition of lithium perchlorate further reduces the already low percentage of enol present. A similar situation is observed when acetylacetone itself acts as the solvent for lithium and sodium perchlorates. In this case, as the salt concentration is increased, ionic clusters are formed composed of metal perchlorate–β-diketone aggregates, clusters whose composition varies as more salt is added. These observations, taken as a whole, provide a clearer picture of the penetrating power of Coulombic fields in hydrophobic media and in fused salts.

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Supporting Information Available: Infrared spectra of **1** in Et_2O and LPDE solutions and infrared spectra of $LiClO_4$–acetylacetone and $NaClO_4$–acetylacetone solutions (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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