for **10a**. The deuterio derivative was prepared by treatment of the copper–phosphazene intermediate with DO-*i*-C_3H_7.[17] Incorporation of the deuterium was confirmed by ^{31}P NMR spectroscopy (J_{PD} = 87 Hz in THF) and electron-impact mass spectrometry (>86% D). After treatment with trifluoroethoxide or phenoxide, the product was nondeuterated **5**.

Reactions of 5 with Excess Chlorine. The following procedure is typical. Compound **5a** was dissolved in CCl_4 (25 mL), and chlorine was bubbled through the solution for 5 min at 0 °C. The ^{31}P NMR spectrum of the solution was compatible with a 100% conversion of **5** to **9** after this time. The mixture was stirred for 1 h, the solvent was removed, and the product was purified by filtration of a solution in CH_2Cl_2 through neutral alumina to give **9a** (53%). The yields of compounds **9b–d** were 70, 45, and 74%, respectively.

Reactions of 2a and 2b with Excess Chlorine. The following is a typical procedure. Excess chlorine was bubbled for 24 h through a solution of **2a** (3.0 g, 5.2 mmol) in CCl_4 (125 mL). A ^{31}P NMR spectrum at this stage was indicative of unreacted **2a** only. Similarly, no reaction was evident following ultraviolet irradiation. However, at reflux temperature in CCl_4, **2a** underwent chlorination to yield $N_3P_3Cl_5(CH_3)$ (1.0 g, 61%). This product was identified by comparison with an authentic sample prepared by another route.[31] Compound **2b** did not react under the same conditions. No reaction could be detected with excess bromine at 25 °C after 24 h.

Reactions of 2a or 2b with Sodium Trifluoroethoxide or Phenoxide in the Presence of CCl_4. All of these reactions were carried out in a similar manner. Table II contains a summary of specific reaction conditions. A solution of **2b** (4.0 g, 5.7 mmol) in 1:1 v/v THF/CCl_4 (100 mL) was added slowly to a solution of sodium trifluoroethoxide. The reaction mixture was then stirred for 24 h at 24 °C. The mixture was poured into water (200 mL) and was extracted with diethyl ether (2 × 250 mL). The extract was dried over $MgSO_4$, and the solvent was removed at reduced pressure to leave crude **3b**. This was purified by filtration of a solution in CH_2Cl_2 through neutral alumina to give **3b** as an oil (6.9 g, 86%). In the reactions of **2a** or **2b** with sodium phenoxide, excess phenol was removed by sublimation at 50 °C (0.02 torr) during the purification process and the products were separated by fractional recrystallization from diethyl ether.

Attempted Reactions of 6a with Sodium Trifluorethoxide or Phenoxide in the Presence of CCl_4. These reactions were incomplete because of the more facile reaction of the sodium alkoxide or aryl oxide with CCl_4 at the elevated temperatures needed for these interactions. After removal of unreacted material, small amounts of cyclic trimeric P–P cleavage products were detected.

Acknowledgment. We thank the Office of Naval Research for the support of this work. We also acknowledge the helpful comments of C. DeBrosse with respect to the NMR analyses and J. Zarian and L. Mosher for obtaining the Raman spectra.

Registry No. 1, 940-71-6; **2a**, 80241-37-8; **2b**, 21229-71-0; **3a**, 75155-07-6; **3b**, 81098-36-4; **3c**, 75155-13-4; **3d**, 81098-37-5; **3e**, 81098-38-6; **3f**, 81098-39-7; **5a**, 81098-40-0; **5b**, 81098-41-1; **5c**, 81098-42-2; **5d**, 81098-43-3; **6a**, 81098-44-4; **6b**, 81120-75-4; **7a**, 81098-45-5; **7b**, 81098-46-6; **8a**, 81098-47-7; **8c**, 81098-48-8; **9a**, 81098-49-9; **9b**, 81098-50-2; **9c**, 81098-51-3; **9d**, 81098-52-4; **10a**, 68351-74-6; **10b**, 81098-53-5; $N_3P_3(OC_6H_5)_4(C_6H_5)Cl$, 81098-52-4; $[N_3P_3(OPh)_4(CH_3)][N_3P_3(OPh)_4(C_4H_9)]$, 81098-54-6; $[N_3P_3Cl_4(CH_3)][N_3P_3Cl_4(C_4H_9)]$, 81098-55-7; $NaOCH_2CF_3$, 420-87-1; $NaOC_6H_5$, 139-02-6; $NaOCH_2CH_3$, 141-52-6; allyl bromide, 106-95-6.

Supplementary Material Available: A compilation of infrared characterization data; Table III, characterization data including melting point, mass spectral, and elemental analysis data; Appendix A, an interpretation of the ^1H NMR couplings in the spectra of **2a** and **6a**, and Appendix B, an interpretation of the ^{31}P NMR couplings in the spectra of **6a** and **6b** (7 pages). Ordering information is given on any current masthead page.

(31) Allcock, H. R.; Harris, P. J. *Inorg. Chem.* **1981**, *20*, 2844.

(32) Letcher, J. H.; Van Wazer, J. R. *Top. Phosphorus Chem.* **1967**, *5*, 247.

(33) For comparison, an asymmetric bi(cyclophosphazene) $[N_3P_3(OPh)_4(CH_3)][N_3P_3(OPh)_4(n\text{-}C_4H_9)]$ was prepared from $[N_3P_3Cl_4(CH_3)][N_3P_3Cl_4(n\text{-}C_4H_9)]$ by the method used to prepare **6a**. This compound showed a parent ion at 1086 amu in the mass spectrum and absorbances at 1200 (s), 1175 (sh), and 1160 cm^{-1} (ν(PN)) in the infrared spectrum. The 81.0-MHz ^{31}P NMR spectrum was not expected to exhibit such a high degree of "deceptive simplicity" due to asymmetry which would make the sets of P(P)R and $P(OPh)_2$ nuclei nonchemical shift equivalent. The spin system was interpreted as M_2ABN_2. The A and B resonances were multiplets centered at 31.81 and 32.38 ppm, respectively, while the M and N parts of the spin system were centered at 7.43 and 7.75 ppm (from the $[N_3P_3(OPh)_4(CH_3)]$ and $[N_3P_3(OPh)_4(n\text{-}C_4H_9)]$ fragments), respectively. Interestingly, the M part was a 1:2:1 triplet, while the N part was a 1:1:1:1 quartet and each part was "deceptively simple". The average coupling $N = |J_{PNP} + J_{PPNP}|$ was found to be 25.6 and 20.4 Hz for the M and N parts of the spin system. The value of N for the M part ($[N_3P_3(OPh)_4(CH_3)]$) of the spin system agrees closely to that found for **6a** (26.5 Hz). An analysis of this part of the spin system indicated that $J_{MB} = J_{PPNP} \simeq 7.4$ Hz and $|J_{PP}| > 168$ Hz. This is also consistent with the respective couplings determined for **6a**.

(34) No parent ion was observed in the high-resolution mass spectra of **9a** and **9b** due to the difficulty of resolution needed to separate it from fragment ions of perfluorokerosene at 580.9633 and 642.9601 amu, respectively. However, a parent ion was observed for ^{37}Cl-substituted **9b** at 644.9575 amu (calcd 644.9586 amu).

Decarbonylation of Tetrahydrofuran-2-carboxylic Acids and Tetrahydropyran-2-carboxylic Acids in Concentrated Sulfuric Acid: Formation of Oxonium Ions

Hans Aaron Bates

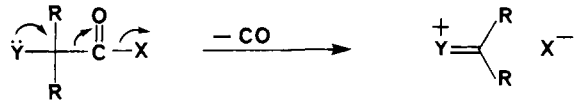
Contribution from the Department of Chemistry, State University of New York at Stony Brook, Stony Brook, New York 11794. *Received October 12, 1981*

Abstract: Tetrahydrofuran-2-carboxylic acids **1**, **3**, and **5** readily decarbonylate in 96% sulfuric acid, generating stable oxonium ions **2**, **4**, and **6**, respectively. Analogously, tetrahydropyran-2-carboxylic acids **7**, **9**, **12**, and **14a** produce oxonium ions **8**, **10**, **13**, and **15**, respectively. These oxonium ions are quite stable, with the exception of **10**, which partially isomerizes to **11**, and **13**, which rearranges to ions **17** and **21**. Details in the transformation of oxonium ion **15** into lactone **23** by way of open chain acid **22a** were elucidated.

Unsaturated oxonium ions are important intermediates in numerous reactions and have been prepared by a variety of methods.[1] The synthetic utility of unsaturated oxonium ions resides in their reactivity with oxygen and carbon nuleophiles. It occurred to us

0002-7863/82/1504-2490$01.25/0

Scheme I



that under certain conditions α-alkoxy carboxylic acids or their derivatives might possibly decarbonylate to afford oxonium ions (Scheme I, Y = OR), a process analogous to the known facile decarbonylation of tertiary α-amino acid chlorides to iminium salts (Scheme I, Y = NR_2).[2] Although the α-alkoxy acid chlorides apparently do not generally decarbonylate with equal facility (various stable α-alkoxy acid chlorides have been prepared and even distilled without decomposition[3]), we were encouraged to investigate this reaction by a report that methoxyacetyl chloride ejects carbon monoxide when treated with SbF_4–SO_2.[4] In addition, the conversion of cineolic acid (**14a**) to lactone **23** in the presence of concentrated sulfuric acid involves loss of carbon monoxide,[5] while decarbonylation followed by carbonylation has been proposed in the rearrangement of cinenic acid (**12**).[6]

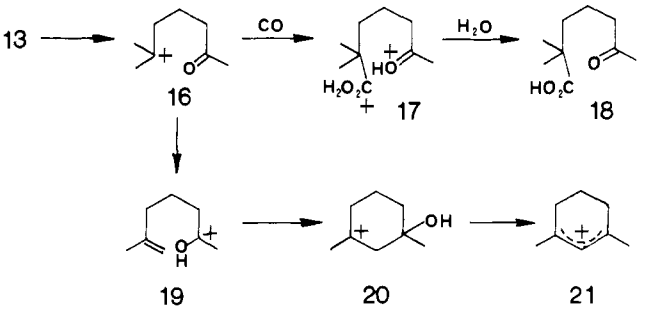
Various carboxylic acids undergo decarbonylation in highly acidic media when the resulting carbonium ions possess particular stability. For example, pivalic acid and triphenylacetic acid decarbonylate to afford *tert*-butyl cation and triphenylmethyl cation, respectively.[7] Additionally, the facile decarbonylation of α-hydroxyl carboxylic acids to protonated ketones (Scheme I, Y = OH)[7] afforded a close analogy for the desired transformation. Thus we reasoned that the stability of the resulting oxonium ions should make the decarbonylation of α-alkoxy carboxylic acids a favorable process.

In the present investigation, we have examined the decarbonylation of a series of tetrahydrofuran-2-carboxylic acids and tetrahydropyran-2-carboxylic acids and have reinvestigated the formation of lactone **23** from cineolic acid (**14a**).

Results and Discussion

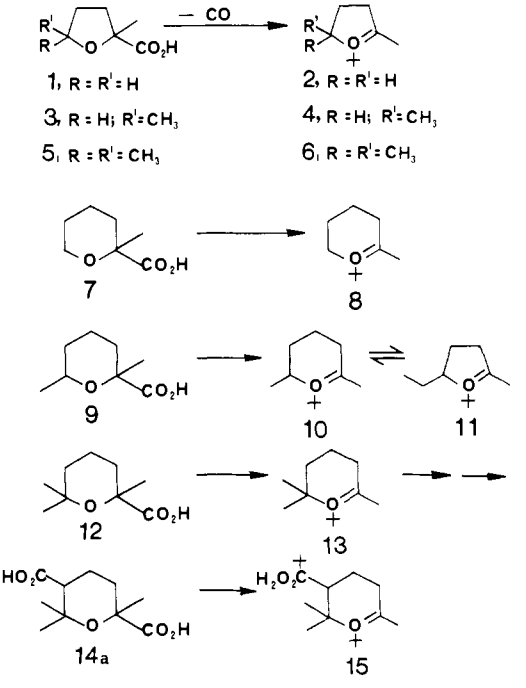
The requisite tetrahydrofuran-2-carboxylic acids, **1**,[8] **3**,[9] and **5**, were prepared by hydrolysis of the corresponding tetrahydrofuran-2-carbonitriles, which were obtained by intramolecular reaction between the hydroxyl of a cyanohydrin and a halide, hydroxyl, or vinyl group. Tetrahydro-2,6,6-trimethyl-2*H*-pyran-2-carboxylic acid (cinenic acid, **12**) was prepared analogously by treating 6-hydroxy-6-methyl-2-heptanone with hydrogen cyanide.[7] Although **7** and **9** had been prepared by treating the appropriate bromoketones with cuprous cyanide and subsequent hydrolysis,[7] we found it more practical to prepare these compounds by catalytic reduction of the readily available dihydropyran

Scheme II



Diels–Alder adducts.[10] *cis*-Tetrahydro-2,6,6-trimethyl-2*H*-pyran-2,5-dicarboxylic acid (cineolic acid, **14a**) was prepared by the inveterate permanganate oxidation of cineole.[6]

With the desired tetrahydrofuran-2-carboxylic acids and tetrahydropyran-2-carboxylic acids in hand, we proceeded to investigate whether decarbonylation would indeed occur. When any of these acids was mixed with 96% sulfuric acid at 20 °C, we were gratified to observe a rapid evolution of carbon monoxide. After gas evolution ceased, ^{1}H NMR revealed that tetrahydrofuran-2-carboxylic acids **1**, **3**, and **5** had been transformed exclusively into oxonium ions **2**, **4**, and **6**, respectively, spectroscopically identical with independently prepared samples.[1e,11] Analogously, decarbonylation of 2-methyltetrahydro-2*H*-pyran-2-carboxylic acid (**7**) afforded only oxonium ion **8**.[12] All of these oxonium salts were quite stable in concentrated sulfuric acid; no decomposition or rearrangement was evident after several weeks at 20 °C.[11]



Decarbonylation of the remaining tetrahydropyran-2-carboxylic acids proved to afford more complex products. Thus decarbonylation of **9** yielded a 1:1 mixture of tetrahydropyranyl cation **10** and tetrahydrofuranyl cation **11**. Evidently **10** is the initial product, but it rapidly equilibrates to **11** via a 1,2-hydride shift, as Brouwer's detailed investigations have documented.[11a] Presumably, had **11** been independently prepared by decarbonylation of 5-ethyl-2-methyl-tetrahydrofuran-2-carboxylic acid, it would

(1) For reviews and leading references see: (a) Perst, H. "Oxonium Ions in Organic Chemistry"; Academic Press: New York, 1971. (b) Perst, H. In "Carbonium Ions"; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley-Interscience: New York, 1976; Vol. 5, p 1961. (c) Olah, G. A. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 173. (d) Quirk, R. P.; Gambill, C. R.; Thyvelikakth, G. X. *J. Org. Chem.* **1981**, *46*, 3181. (e) Pittman, C. U.; McManus, S. P. *J. Am. Chem. Soc.* **1969**, *91*, 5915.

(2) (a) Dean, R. T.; Rapoport, H. *J. Am. Chem. Soc.* **1976**, *98*, 7448. (b) Wasserman, H. H.; Tramper, A. W. *Tetrahedron Lett.* **1977**, 1449. (c) Weinstein, B.; Craig, A. R. *J. Org. Chem.* **1976**, *41*, 875.

(3) (a) Richardson, W. H.; Koskinen, W. C. *J. Org. Chem.* **1973**, *38*, 1173. (b) El-Abadelah, M. M. *Tetrahedron*, **1973**, *29*, 589. (c) Weinhaus, H.; Sorge, H. *Chem. Ber.* **1913**, *46*, 1927. (d) In contrast, 2-methyl-1,3-dioxolane-2-carbonyl chloride does lose carbon monoxide: Newman, M. S.; Chen, C. H. *J. Org. Chem.* **1973**, *38*, 1173.

(4) Olah, G. A.; Bollinger, J. M. *J. Am. Chem. Soc.* **1967**, *89*, 2993.

(5) (a) Wallach, O. *Justus Liebigs Ann. Chem.* **1890**, *258*, 319. (b) Rupe, H.; Lotz, W. *Chem. Ber.* **1906**, *39*, 4083. (c) Rae, I. D.; Redwood, A. M. *Aust. J. Chem.* **1974**, *27*, 1143. (d) We thank John E. Brenton of this laboratory for preparing a sample of cineolic acid.

(6) (a) Rupe, H.; Schlochoff, P. *Chem. Ber.* **1905**, *38*, 1499. (b) Rupe, H.; Liechtenhan, C. *Ibid.* **1908**, *41*, 1278. (c) Meinwald, J.; Hwang, H. C.; Christman, D.; Wolf, A. P. *J. Am. Chem. Soc.* **1960**, *82*, 483. (d) Meinwald, J.; Grossman, R. F. *Ibid.* **1956**, *78*, 922. (e) Meinwald, J.; Yankeelov, J. A. *Ibid.* **1958**, *80*, 5266.

(7) For a review of carboxylic acid decarbonylations, see: Ropp, G. A. *J. Am. Chem. Soc.* **1960**, *82*, 842.

(8) Leroux, Y. *Bull. Soc. Chim. Fr.* **1968**, 344.

(9) Colonge, J.; Lagier, A. *Bull. Soc. Chim. Fr.* **1949**, 24.

(10) (a) Smith, C. W.; Norton, D. G.; Seaver, A. B. *J. Am. Chem. Soc.* **1951**, *73*, 5270. (b) Mundy, B. P.; Otzenberger, R. D.; DeBernardis, R. A. *J. Org. Chem.* **1971**, *36*, 2390.

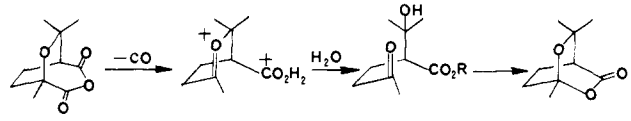
(11) (a) Brouwer, D. M. *Recl. Trav. Chim. Pays-Bas* **1969**, *88*, 530. (b) Pittman, C. U.; McManus, S. P. *Chem. Commun.* **1968**, 1479.

(12) Deno, N. C.; Billups, W. E.; Kramer, K. E.; Lastomirsky, R. R. *J. Org. Chem.* **1970**, *35*, 3080. The ^{1}H NMR signal for $CH_3C{=}O{-}$ of **8** is mistakenly quoted by Deno et al. as δ 2.48 rather than δ 2.85.

likewise have undergone equilibration to **10**. In contrast, absence of interconversion between **4** and **8** under the same conditions may be attributed to a less favorable 1,2-hydride shift.

Our attention was now turned to the reaction of cinenic acid (**12**) with sulfuric acid. This reaction was first encountered at the turn of the century by Rupe, who correctly identified the major product as 2,2-dimethyl-6-oxoheptanoic or "geronic" acid (**18**).[7a,7b] Nonetheless, the mechanism remained obscure until elaborate and extensive studies utilizing labeled carbon monoxide enabled Meinwald to propose the intermediacy of oxonium ion **13** as shown in Scheme II.[7c] We now report that oxonium ion **13**[11a] can be directly observed by ^{1}H NMR as a transient intermediate during the first 5 min of reaction. In marked contrast to tetrahydrofuranyl cation **6** which is completely stable, **13** underwent the known rearrangement to 1,3-dimethylcyclohexenyl cation (**21**)[11a] and also afforded **17** by recombining with carbon monoxide. Interestingly, reaction of **16** with carbon monoxide is so facile that it can only be partially suppressed but not prevented by conducting the reaction in vacuo or with a nitrogen sweep.

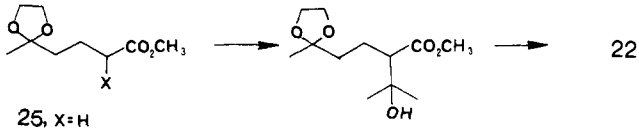
Finally we investigated the decarbonylation of cineolic acid (**14a**) and cineolic anhydride (**14b**), known to produce bicyclic lactone **23**.[6] We were interested in investigating the details of



14b 15 22a, R=H 23
b, R=CH₃

this transformation, whether an oxonium ion could be observed and at what stage cyclization occurred. Indeed, when **14a** or **14b** was dissolved in 96% sulfuric acid, rapid decarbonylation afforded oxonium ion **15** which was observable by ^{1}H NMR and was stable for several hours at room temperature. The stability of **15** compared to **13** may be attributed to the decreased stability of a carbonium ion intermediate analogous to **16** derived from oxonium ion **15**. In addition, **15** displayed no tendency to cyclize to lactone **23** in concentrated sulfuric acid. Neither did cyclization to **23** occur when the reaction was quenched with water. Rather, hydrolysis of **15** afforded acyclic hydroxy keto acid **22a**, the structure of which was verified by synthesis (vide infra). When **22a** was extracted into an organic solvent and dried, however, spontaneous cyclization occurred quite readily.

In order to verify the structure of **22a**, which was not isolable as such, we prepared an authentic sample by independent synthesis. Thus 5-oxohexanoic acid (**24**)[13] was esterified and ketalized to afford **25**. The lithium enolate of **25** was generated with lithium



25, X=H
26, X=I
27

dicyclohexylamide[14] or more efficiently with lithium diisopropylamide and treated with iodine to form **26**. A subsequent Reformatsky reaction between **26** and acetone provided **27** which was deketalized and hydrolyzed to afford **22a**, in all respects (including generation of **23**) identical with **22a** produced by decarbonylation of **14a**.

In summary, we have demonstrated that decarbonylation of tetrahydrofuran-2-carboxylic acids and tetrahydropyran-2-carboxylic acids is a general reaction which produces frequently stable oxonium ions. Investigations aimed at utilizing these reactive intermediates are currently being pursued in this laboratory.

Experimental Section

General Procedures. Proton NMR spectra were recorded at 60 MHz with a Varian EM360 spectrometer. Spectra of oxonium ions were recorded in 96% H_2SO_4 using an external concentric capillary containing 5% Me_4Si in CCl_4 as a reference. IR spectra were recorded by using a Unican SP1000 spectrophotometer. Low-resolution mass spectra were recorded by using a Hewlett-Packard 5984A spectrometer and high-resolution mass spectra were recorded by using a Kratos MS-30 spectrometer. Reactions were generally conducted under a nitrogen atmosphere using magnetic stirring. Organic solutions were dried over anhydrous $MgSO_4$ unless otherwise stated, and solvents were evaporated in vacuo by using a rotary evaporator.

5-Hydroxy-5-methyl-2-hexanone. 5-Methyl-5-hexen-2-one[15] (5.0 g, 41.7 mmol) was stirred 1 h with 3.6 M H_2SO_4 (50 mL) and the mixture then extracted four times with ether. The organic layer was rinsed with saturated K_2CO_3 and dried over Na_2SO_4. Evaporation of the ether afforded 5.04 g (87%) of the crude product.

A pure sample obtained by Kugelrohr distillation (110–130 °C (10 mm)) was identical with authentic material prepared by oxidation of 2-methyl-2,5-hexanediol with Jones reagent.[16a,b] ^{1}H NMR indicates that the product exists partially as the cyclic hemiketal, tetrahydro-2,5,5-trimethyl-2-furanol:[16c] ^{1}H NMR ($CDCl_3$) δ 1.16 (s, CH_3), 1.2–1.5 (m, CH_2CH_2), 1.69 (t, CH_2), 2.10 (s, $COCH_3$), 2.50 (t, $COCH_2$).

Tetrahydro-2,5,5-trimethylfuran-2-carbonitrile. Crude 5-hydroxy-5-methyl-2-hexanone (3.63 g, 27.9 mmol) and anhydrous liquid HCN (1.92 g, 71.1 mmol) were sealed in a glass pressure bottle and heated to 55 °C for 6 h. The excess HCN was allowed to evaporate in an efficient hood, and the product was dissolved in ether and dried. The ether was evaporated, and the residue was carefully kugelrohr distilled (70–95 °C (5 mm)) to afford the nitrile (1.30 g, 33% yield). The yield was the same when distilled 5-hydroxy-5-methyl-2-hexanone was used: NMR ($CDCl_3$) δ 1.18 (3 H, s), 1.34 (3 H, s), 1.52 (3 H, s), 1.7–2.5 (4 H, m); mass spectrum, *m/e* 124.0767 (13%, M − CH_3, calcd 124.0763), 113.0968 (100%, M − CN, calcd 113.0967), 97 (21%), 95 (26%).

Tetrahydro-2,5,5-trimethylfuran-2-carboxylic Acid (5). Tetrahydro-2,5,5-trimethylfuran-2-carbonitrile (220 mg, 1.58 mmol) was refluxed for 12 h with KOH (100 mg, 1.78 mmol) in methanol (1 mL) and water (30 mg, 1.67 mmol). The methanol was evaporated and the residue extracted between ether and water. The ether layer afforded, after drying and evaporation, the crystalline tetrahydro-2,5,5-trimethylfuran-2-carboxamide (108 mg, 44% yield): mp 76–79 °C; NMR ($CDCl_3$) δ 1.23 (6 H, s), 1.40 (3 H, s), 1.5–2.6 (4 H, m), 6.6 (2 H, br s).

The aqueous phase was carefully acidified to pH 2 with concentrated HCl and extracted thrice with ether to afford **5** (88 mg, 35% yield) after Kugelrohr distillation (85–105 °C (1 mm)). Additional **5** was prepared by hydrolyzing the carboxamide for 4 h in refluxing aqueous 3 M NaOH (56% yield): NMR ($CDCl_3$) δ 1.28 (3 H, s), 1.31 (3 H, s), 1.47 (3 H, s), 1.5–2.8 (4 H, m), 8.9 (1 H, s); mass spectrum, *m/e* 143 (2%, M − CH_3), 125 (8%), 113.0959 (100%, M − CO_2H, calcd 113.0967).

Tetrahydro-2-methyl-2*H*-pyran-2-carboxylic Acid (7). Methyl 3,4-dihydro-2-methyl-2*H*-pyran-2-carboxylate[10a] (1.15 g) in methanol (12 mL) was hydrogenated in a shaker at 50 atm for 18 h over platinum catalyst (115 mg). Kugelrohr distillation (100–120 °C (18 mm)) afforded the tetrahydropyran (840 mg, 72% yield). This was hydrolyzed in 1 M NaOH (8 mL). After 4 h, the solution was acidified with concentrated HCl and extracted thrice into ether. Kugelrohr distillation (100–120 °C (18 mm)) afforded **7**[7] (581 mg, 73% yield): ^{1}H NMR ($CDCl_3$) δ 1.42 (3 H, s), 1.4–2.0 (4 H, m), 3.70 (2 H, m), 7.5 (1 H, br s); mass spectrum, *m/e* 99.0821 (100%, M − CO_2H, calcd 99.0810), 43 (99%).

2,3,4,5-Tetrahydro-6-methylpyrylium (8). Carboxylic acid **7** (50 mg) was mixed with 96% H_2SO_4 (0.3 mL) in an NMR tube. After 5–10 min, when carbon monoxide evolution had ceased, the spectrum was observed: ^{1}H NMR (H_2SO_4) δ 2.06 (4 H, m), 2.85 (3 H, s), 3.40 (2 H, m, $CH_2C{=}O^+$), 5.30 (2 H, br t, $CH_2{-}O$).[12]

Tetrahydro-2,6-dimethyl-2*H*-pyran-2-carboxylic Acid (9). Methyl 3,4-dihydro-2,6-dimethyl-2*H*-pyran-2-carboxylate[10b] (1.00 g) in acetic acid (8 mL) was hydrogenated at 50 atm for 8 h by using a platinum

(13) Stetter, H.; Diedrichs, W. *Chem. Ber.* **1952**, *85*, 61. We thank Ping-Nan Deng of this laboratory for a generous sample of 5-oxohexanoic acid.

(14) Rathke, M. W.; Lindert, A. *Tetrahedron Lett.* **1971**, 3995. Repeated attempts to form the corresponding bromide resulted in considerable contamination with unreacted starting material (**25**) formed by proton transfer from **26**.

(15) (a) Schechter, M. S.; Green, N.; LaForge, F. B. *J. Am. Chem. Soc.* **1949**, *71*, 3165. (b) Kimel, W.; Cope, A. C. *Ibid.* **1943**, *65*, 1992.

(16) (a) Youngman, E. A.; Rust, F. F.; Coppinger, G. M.; De La Mare, H. E. *J. Org. Chem.* **1963**, *28*, 144. (b) Surzur, J.-M.; Teissier, P. *Bull. Soc. Chim. Fr.* **1970**, 1611. (c) Nikishin, G. I.; Glukhovtsev, V. G.; Spektor, S. S.; Lubuzh, E. D. *Bull. Acad. Sci. USSR Div. Chem. Sci.* (*Engl. Transl.*) **1973**, 684. Nikishin et al. claim that 5-hydroxy-5-methyl-2-hexanone does not tautomerize to the hemiketal.

catalyst (100 mg). The catalyst was removed and the solvent evaporated. The residue was dissolved in ether, rinsed with water, saturated Na_2CO_3, and saturated NaCl, and then dried over Na_2SO_4. Kugelrohr distillation (110–130 °C (11 mm)) afforded the tetrahydropyran (580 mg, 57% yield). This was hydrolyzed as above to afford **9**[8] in 77% yield after Kugelrohr distillation (120–140 °C (4 mm)): ^{1}H NMR ($CDCl_3$) δ 1.16 (3 H, d), 1.45 (3 H, s), 1.5–1.9 (6 H, m), 3.65 (1 H, m), 7.65 (1 H, br s); mass spectrum, *m/e* 113.0973 (100%, M – CO_2H, calcd 113.0967), 43 (76%).

Treatment of tetrahydro-2,6,6-trimethyl-2*H*-pyran-2-carboxylic acid (12) with sulfuric acid in an open NMR tube resulted in little carbon monoxide evolution. After 5 min, ^{1}H NMR revealed a mixture of cations **13**, **17**, and **21**.[11a] After 30 min, **13** had disappeared leaving **17** and **21** (2.5:1). When the same reaction was conducted in vacuo or with a vigorous nitrogen sweep, the ratio was 1:1 and in a sealed tube, in the presence of 1 equiv of excess carbon monoxide (generated in situ from formic acid), the ratio was 6:1.

Authentic **17** was prepared by dissolving **18**[7] in 96% H_2SO_4: ^{1}H NMR δ 1.48 (6 H, s), 1.83 (4 H, m), 2.89 (3 H, s), 3.19 (2 H, m).

1,5,5-Trimethyl-2,6-dioxabicyclo[2.2.2]octan-3-one (23). A. Cineolic acid (*cis*-tetrahydro-2,6,6-trimethyl-2*H*-pyran-2,5-dicarboxylic acid, **14a**) was prepared by alkaline permanganate oxidation of cineole (eucalyptol) and converted to cineolic anhydride (**14b**) by refluxing with acetic anhydride.[6] Decarbonylation of **14b** with concentrated H_2SO_4, extraction into ether, and Kugelrohr distillation (100–130 °C (1 mm)) afforded a 70% yield of crystalline **23**.[6] Decarbonylation of a sample of dicarboxylic acid **14a** which was contaminated with considerable oxalic acid afforded **23** in 11% yield.

When **14a** or **14b** was decarbonylated in an NMR tube, oxonium ion **15** could be observed directly: ^{1}H NMR (H_2SO_4) δ 1.89 (3 H, s), 1.96 (3 H, s), 2.4 (2 H, m), 2.90 (3 H, br s), 3.26 (2 H, t).

B. Ketal **27** was hydrolyzed to **22b** with 2:1 acetone–1 M HCl for 20 min. Most of the acetone was evaporated, and the ester was hydrolyzed by addition of 1 M NaOH. After 15 min, the solution was acidified, saturated with NaCl, and extracted with ether. The yield of **23** after distillation was 74%.

2-(1-Hydroxy-1-methylethyl)-5-oxohexanoic Acid (22a). A. Lactone **23** was dissolved in D_2O. The NMR spectrum indicated that hydrolysis to **22a** had occurred: ^{1}H NMR (D_2O) δ 1.21 (6 H, s), 1.4–2.0 (2 H, m), 2.10 (3 H, s), 2.2–2.6 (3 H, m).

The hydroxyacid **22a** did not revert to lactone **23** in D_2O or 2 M D_2SO_4 but did recyclize to **23** when extracted into ether and dried over Na_2SO_4.

B. Hydrolysis of ketal ester **27** as described for the preparation of **23** initially produced **22a** which cyclized during the workup procedure.

Methyl 5-Oxohexanoate Ethylene Ketal (25). 5-Oxohexanoic acid **24**[13] 3.30 g, 25.4 mmol) was esterified with methanol (35 mL) and H_2SO_4 (0.1 mL). After 18 h, most of the methanol was evaporated, the residue was dissolved in ether and rinsed with dilute K_2CO_3, water, and saturated NaCl, and then dried. The ether was evaporated leaving the methyl ester (3.41 g, 94% yield).

The methyl ester (3.10 g, 21.5 mmol) was refluxed for 3.5 h in benzene (30 mL) with ethylene glycol (2.0 g, 32 mmol, 150 mol%) and *p*-toluenesulfonic acid (30 mg, 0.16 mmol, 0.7 mol%) beneath a Dean–Stark trap. The benzene solution was rinsed with saturated aqueous Na_2CO_3, and the aqueous layer was extracted twice with ether. The combined organic phases were rinsed with water and saturated NaCl, dried, concentrated, and then Kugelrohr distilled (110–140 °C (4 mm)) to afford **25** (3.47 g, 86% yield): ^{1}H NMR ($CDCl_3$) δ 1.28 (3 H, s), 1.5–1.8 (4 H, m), 2.25 (2 H, m), 3.53 (3 H, s), 3.82 (4 H, s); mass spectrum, *m/e* 173.0816 (22%, M – CH_3, calcd 173.0814), 157 (10%, M– OCH_3), 99 (35%), 87.0444 (100%, M – $CH_2CH_2CH_2CO_2CH_3$, calcd 87.0446).

Methyl 2-Iodo-5-oxohexanoate Ethylene Ketal (26). Butyllithium (7.0 mL, 1.6 M in hexane, 11.2 mmol) was added to diisopropylamine (1.7 mL, 12.1 mmol) in THF (15 mL) at 0 °C. After 15 min, the ester (**21**) (1.59 g, 8.46 mmol) was added over 5 min at −78 °C. One hour later, this ester enolate solution, still at −78 °C, was added over 15 min to a solution of I_2 (2.6 g, 10.2 mmol) in THF (10 mL) at −78 °C by using a cannula. After 15 min at −78 °C, the mixture was warmed to 20 °C and the solvent was evaporated. The residue was partitioned between water and ether, and the ether layer was rinsed with saturated sodium thiosulfate, 1 M HCl, saturated Na_2CO_3, and saturated NaCl, dried, concentrated, and rapidly Kugelrohr distilled (100–130 °C (0.2 mm)) to afford the somewhat unstable iodide (2.15 g, 81% yield) which was immediately utilized in the next step: ^{1}H NMR ($CDCl_3$) δ 1.30 (3 H, s), 1.5–2.3 (4 H, m), 3.63 (3 H, s), 3.84 (4 H, s), 4.30 (1 H, t).

Methyl 2-(1-Hydroxy-1-methylethyl)-5-oxohexanoate Ethylene Ketal (27). The iodide (**26**) (1.87 g, 5.95 mmol) was dissolved in dry benzene (10 mL), and freshly filed zinc powder (700 mg, 10.7 mmol) was added, followed by acetone (700 mg, 12.1 mmol). A strongly exothermic reaction commenced, and the mixture was refluxed for 30 min and then cooled and quenched with saturated NH_4Cl. The aqueous phase was extracted thrice with ether, the organic phase was dried, and the ether was evaporated to afford the crude product contaminated with a small amount of **25**. Kugelrohr distillation (100–130 °C (0.25 mm)) afforded the product (702 mg, 48% yield): ^{1}H NMR (CDC_3) δ 1.23 (6 H, s), 1.30 (3 H, s), 1.5–1.9 (4 H, m), 2.31 (1 H, m), 2.65 (1 H, br s), 3.60 (3 H, s), 3.82 (4 H, s); mass spectrum, *m/e* 99 (33%), 87 (100%), 59 (15%), 55 (15%).

Methyl 2-(1-hydroxy-1-methylethyl)-5-oxohexanoate (22b). The ketal (**27**) (21 mg, 0.085 mmol) was hydrolyzed with acetone (0.40 mL) and 1 M HCl (0.20 mL). After 20 min, ether and saturated aqueous Na_2CO_3 were added, and the aqueous phase was extracted twice more with ether. The organic phases were combined, dried, and concentrated. The residue was Kugelrohr distilled (110–130 °C (1 mm)) to afford the product (11 mg, 64%): ^{1}H NMR ($CDCl_3$) δ 1.20 (6 H, s), 1.5–2.0 (2 H, m), 2.06 (3 H, s), 2.1–2.6 (3 H, m), 3.60 (3 H, s).

Acknowledgment. I gratefully acknowledge the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research, and I thank Professor Raphael Mechoulam of the Hebrew University in Jerusalem for a stimulating discussion which engendered this investigation.

Registry No. **1**, 14886-93-2; **2**, 26084-50-4; **3**, 81045-28-5; **4**, 22065-54-9; **5**, 81027-80-7; **6**, 26084-53-7; **7**, 4180-13-6; **8**, 59582-26-2; **9**, 19679-88-0; **10**, 81027-81-8; **11**, 81027-82-9; **12**, 470-59-7; **13**, 34341-73-6; **14a**, 81027-83-0; **14b**, 4703-74-6; **15**, 81027-84-1; **17**, 81027-85-2; **21**, 38355-98-5; **22a**, 81027-88-5; **22b**, 81027-89-6; **23**, 52866-70-3; **24**, 3128-06-1; **24** methyl ester, 13984-50-4; **25**, 29310-39-2; **26**, 81027-86-3; **27**, 81045-29-6; 5-hydroxy-5-methyl-2-hexanone, 42137-04-2; tetrahydro-2,5,5-trimethylfuran-2-carbonitrile, 81027-87-4; methyl 3,4-dihydro-2-methyl-2*H*-pyran-2-carboxylate, 58293-76-8; methyl 3,4-dihydro-2,6-dimethyl-2*H*-pyran-2-carboxylate, 29765-30-8; 5-methyl-5-hexen-2-one, 3240-09-3; tetrahydro-2,5,5-trimethyl-2-furanol, 81027-90-9; tetrahydro-2,5,5-trimethyl-2-carboxamide, 81027-91-0.