Table I. Reduction of Diazonium Ions in Chloroform

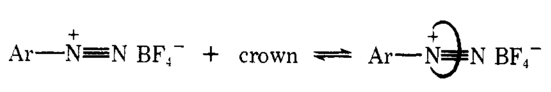
$$Ar{-}N{\equiv}N^+BF_4^- \xrightarrow[\substack{Cu_2O \\ CHCl_3}]{H_3PO_2} ArH$$

Diazonium tetrafluoroborate	Registry no.	Product[a]	% yield[b]	Registry no.
p-Bromobenzene-	673-40-5	Bromobenzene	99	108-86-1
o-Bromobenzene-	10448-07-4	Bromobenzene	99	
p-Chlorobenzene-	673-41-6	Chlorobenzene	97 (90)[c]	108-90-7
o-Chlorobenzene-	1956-97-4	Chlorobenzene	97	
2,4-Dichlorobenzene-	21872-70-8	*m*-Dichlorobenzene	97	541-73-1
p-Methylbenzene-	459-44-9	Toluene	99	108-88-3
3,4-Dimethylbenzene-	2192-34-9	*o*-Xylene	92	95-47-6
p-Methoxybenzene-	459-64-3	Anisole	67[e]/88[d]	100-66-3
p-Nitrobenzene-	456-27-9	Nitrobenzene	99	98-95-3

[a] The identities of products were confirmed by spectral analysis of samples obtained by preparative GLC. [b] Yields were determined by GLC using a 5 ft × 0.25 in. 10% SE-30 on Chromosorb P column utilizing an internal standard and are corrected for detector response. All yields represent at least four replicate experiments and are reproducible to ±2%. [c] Isolated yield. Reaction carried out on a 44-mmol scale using 7 equiv of H_3PO_2. [d] 0.075 equiv of 18-crown-6 added. [e] Extension of the reaction time to 3 h and addition of 14 equiv of H_3PO_2 did not alter the yield.

substituents do not appreciably hinder the reduction. The difficulty encountered in the latter case may be overcome by addition of a small amount of 18-crown-6 polyether.[11] When 0.075 equiv (7.5 mol %) of 18-crown-6 was added to the reducing mixture containing *p*-methoxybenzenediazonium tetrafluoroborate, the yield of reduction product was increased to 88%. It should be noted that neither in the presence or absence of crown were chlorinated or fluorinated by-products isolated.

We presume that the reduction involves aryl radical formation and hydrogen atom capture as proposed by Kornblum and co-workers some years ago.[9b] The crown effect is somewhat more difficult to explain. There are three obvious explanations we have considered. The first is that crown is enhancing the solubility of the diazonium salt, a now well-established phenomenon.[12] The second possibility is that the crown complexed diazonio function is more prone to reduction than the noncomplexed function, an unlikely prospect in light of the recent results reported for the Schiemann reaction.[13] The third possibility is that the crown and copper ion interact to enhance the reduction process. No increase in yield was observed, however, when 15-crown-5 was substituted for 18-crown-6. The smaller crown is of the appropriate size to



complex cuprous or cupric but not diazonium ion. The latter possibility therefore seems unlikely. We are currently considering the two aforementioned and other possibilities, although this in no way affects the efficacy of the method herein reported.

Experimental Section

The diazonium tetrafluoroborates were prepared by standard methods[14] from commercially available anilines. Hypophosphorous acid (50% aqueous, Fisher) was used as obtained. The chloroform used was ACS reagent grade, although substitution of carefully dried, alcohol-free reagent gave identical results.

Reduction Procedure.[15] To a stirred suspension of the diazonium tetrafluoroborate (1.5 mmol) in chloroform (10 mL) cooled in an ice water bath was added 0.80 mL (7.5 mmol) of H_3PO_2 and a few milligrams (trace) of Cu_2O. The mixture was stirred for 5 min, after which time Na_2CO_3 was added continuously until the pH was 8. The mixture was then washed with water and the aqueous layer backwashed with chloroform; the combined organic layers were filtered (if necessary), dried over sodium sulfate, and subjected to GLC analysis.

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Metal Ion Promoted Lactonizations

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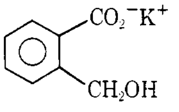
The acid-catalyzed lactonization of hydroxy acids of fixed conformation has been a topic of considerable interest.[1] Alkyl substituents on the aromatic nucleus enhance lactonization rates of derivatives of **1**.[1d] The terms "stereopopulation control" [1b] and "trialkyl lock" [1e] have been applied to methylated

Table I. Lactonization Rates at 25 °C

Compd	Conditions[a]	$10^3 k$, s^{-1}
3	A	6.52 (0.26)[b]
	B	4.57 (0.66)[c]
	C	0.601 (0.117)[d]
4	A	4.37 (0.63)[b]
	B	5.51 (2.43)[c]
	C	0.618 (0.284)[d]

[a] A = 0.01 M $Cu(OAc)_2$ (pH 5.92); B = 0.01 M $CuSO_4$, 0.05 M HOAc, 0.05 M NaOAc; C = 0.02 M $ZnSO_4$ (pH 6.27). [b] Calculated rate at pH 5.92. See ref 2a. [c] Rate in 0.05 M HOAc, 0.05 M NaOAc. [d] Calculated rate at pH 6.27. See ref 2a.

derivatives of **5** to explain rate enhancements in lactonization. Recently increased lactonization rates of methylated derivatives of **5** have been attributed to relief of steric strain.[1f,g] The formation of lactones from the hydroxy acids corresponding to **1**, **3**, **4**, and **5** is catalyzed not only by hydronium ion, but also by general acids and bases in carboxylic acid–carboxylate buffers.[1b,2]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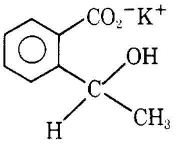
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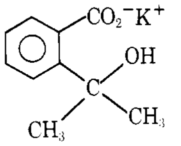
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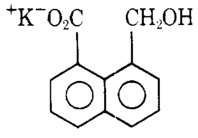
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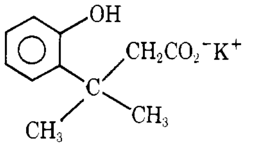
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We now report that the potassium salts **3** and **4** lactonize rapidly under the influence of dilute copper(II) salts. Table I presents lactonization rate data. That the reactions are truly due to metal ion and not acid catalysis is shown by comparison of reaction rates in aqueous media of comparable pH. Figures 1 and 2 show the effect of copper concentration on lactonization rates of **3** and **4**. The varying rates in both buffered and unbuffered media also support the conclusion of a metal ion promoted reaction. Temperature effect studies give an enthalpy of activation of 18.6 kcal/mol and an activation entropy of −6.4 eu for formation of 3,3-dimethylphthalide from **3** in 0.01 M cupric acetate. These values differ significantly from the buffer-catalyzed reaction, characterized by large negative entropies of activation.[2a] Zinc salts also promote these lactonizations, but to a lesser extent than copper.

Potassium salt **1**, when dissolved in copper(II) solutions, gives a complex differing spectrally from either **1** or the corresponding lactone, phthalide. Only upon addition of mineral acid does this complex slowly revert to phthalide. Incorporation of a single methyl group (potassium salt **2**) leads to the observation of a copper-promoted cyclization. Larger copper-promoted rates are seen for the dimethyl-substituted hydroxy acid salt **3**. These observations suggest a hydroxyl group conformation favoring lactonization for the occurrence of copper catalysis.

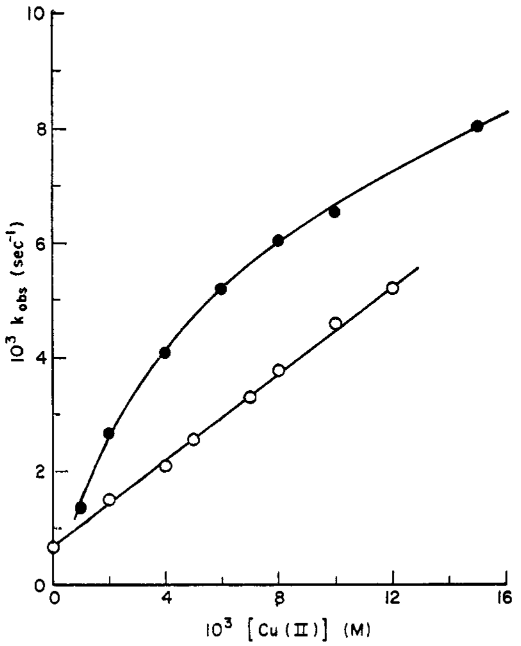


Figure 1. Rates of lactonization of **3** in copper(II) solutions at 25 °C: ●, $Cu(OAc)_2$; ○, $CuSO_4$, 0.05 M HOAc, 0.05 M NaOAc.

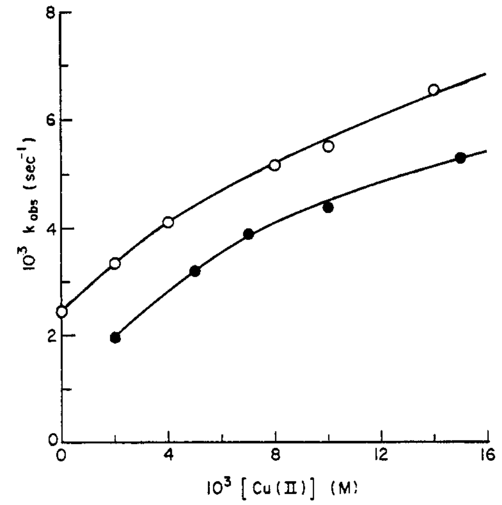


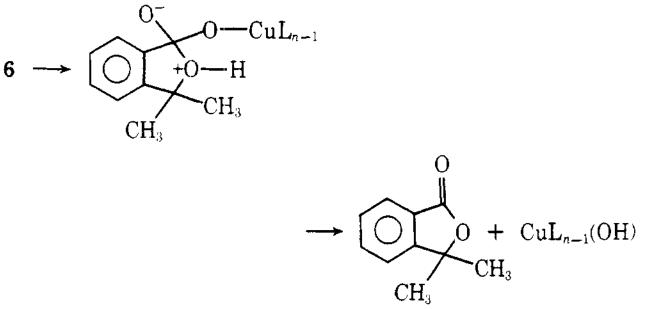
Figure 2. Rates of lactonization of **4** in copper(II) solutions at 25 °C: ●, $Cu(OAc)_2$; ○, $CuSO_4$, 0.05 M HOAc, 0.05 M NaOAc.

Where do these observations fit in the context of metal ion catalyzed hydrolyses? Previously copper and other transition metals have been shown to catalyze hydrolysis of specific amino esters in which the ester is coordinated to the metal ion by way of both the amino group and the ester carbonyl.[3] The carbonyl is "metal activated" toward nucleophilic attack. Coordination with the amino group is necessary for the metal-catalyzed hydrolysis reaction. Hydrolysis of "normal" esters such as ethyl acetate are not metal catalyzed. The metal-promoted cyclizations of **3** and **4** are unusual in that there can be no coordination with nitrogen. The intimate details of the lactonization mechanism therefore cannot be the precise microscopic reverse of the metal-catalyzed hydrolysis of amino esters which involves nitrogen complexed intermediates.

A mechanism consistent with the nonlinear plot of rate as a function of cupric acetate concentration involves reversible displacement of acetate ligand by carboxylate salt. This copper complexed substrate, **6**, is activated toward intramolecular nucleophilic attack by a properly oriented hydroxyl group.[4] Either cyclization or collapse of the tetrahedral intermediate may be rate determining. The nonlinear plot in Figure 1 in cupric acetate solutions is a result of an acetate ion rate suppression as can be shown by addition of excess acetate at constant copper concentration. Also of interest is the rate behavior in buffered solution. In acetic acid–acetate buffers a linear plot of rate vs. copper(II) concentration is observed.

$$CuL_n + RCO_2^- \rightleftharpoons CuL_{n-1}(O_2CR) + L$$

6



However, rates are slower than in unbuffered solutions of comparable copper concentration even though the buffer components are known to catalyze cyclization of the hydroxy acid. Additionally, the pH of the unbuffered solutions (5.8–6.3) is greater than that of the buffered solutions (4.74) and hence cannot account for the increased reactivity in unbuffered media. The rate suppression in buffered media follows from the increased amount of free uncomplexed hydroxy acid and hydroxy acid salt in the buffered medium. In the absence of buffer, more substrate is complexed with copper and hence faster rates are observed.

In contrast, lactonization rates of **4** are faster in buffered media (Figure 2) and rate plots give nonlinear behavior as a function of copper concentration. This is attributed to the presence of significant buffer catalysis in the buffered medium. Such buffer catalysis apparently contributes less to the overall lactonization rate of **3** than for **4**. In general, the effect of carrying out studies in buffered media is to partially obscure the metal ion promoted reaction. Studies show less spectacular catalysis in lactonization of **2** and **5** which are less well aligned for cyclization.

The mechanism suggested is similar to the microscopic reverse of the process proposed by Buckingham for the recently observed metal-catalyzed hydrolysis of propionic anhydride.[5] Our results suggest that copper and zinc ions can promote analogous esterifications when aqueous equilibria strongly favor the synthesis side of the reaction.

Experimental Section

Preparation of Hydroxy Acid Salts. General Procedure. A given amount of the appropriate lactone was saponified by refluxing with 1.05 equiv of potassium hydroxide in methanol. The solvent was removed in vacuo and the dry salt was used for rate measurements.

Preparation of Lactones. The lactones employed were all prepared using literature procedures. Phthalide was prepared by zinc reduction of phthalimide.[6] 3-Methylphthalide was prepared by sodium borohydride reduction of *o*-acetylbenzoic acid. 3,3-Dimethylphthalide was prepared by reaction of methylmagnesium iodide with diethyl phthalate.[7] 1,8-Naphthalide was prepared by cleavage of acenaphthenequinone with potassium hydroxide followed by reduction of the 1,8-naphthaldehydic acid with formaldehyde.[8] 4,4-Dimethylhydrocoumarin was prepared by acid-catalyzed reaction of phenol and methyl 3-methyl-2-butenoate.[9]

Kinetic Procedure. A solution of appropriate concentration of a given hydroxy acid salt in methanol was prepared. Injection of a 0.01-mL aliquot of this solution into a temperature equilibrated cuvette in a constant temperature compartment of a Cary 15 or Gilford 240 spectrophotometer initiated the kinetic run. Changes in absorbances at a given wavelength were monitored as a function of time. Substrate concentrations were typically 10^{-4}–10^{-5} M. Rate constants were calculated by the usual least-squares procedure. For the copper-promoted reactions, rates were monitored at 280–285 nm. At higher copper concentrations, this region becomes obscured by absorbance due to copper. At the copper concentrations employed, rates could be conveniently monitored at these wavelengths. For compounds **4** and **5**, decreases in absorbances were observed as a function of time (disappearance of the copper complex) while **2** and **3** led to absorbance increases. Upon completion of a kinetic run, the spectrum was identical with that of corresponding lactone solutions prepared independently.

Other copper(II) salts also promoted lactonization. However, precipitation of copper(II) hydroxides interferes with spectral measurements and rate determinations. In cupric acetate media or copper(II) sulfate in acetate buffered media, precipitation of copper(II) hydroxides did not present a problem. The following wavelengths were used for monitoring lactonization rates for copper-promoted reactions: **2**, 280 nm; **3**, 283 nm; **4**, 285 nm; **5**, 282 nm. Zinc sulfate promoted reactions of **4** were monitored at 240 nm.

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Registry No.—**3**, 61490-94-6; **4**, 61490-95-7.

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Interconversions in Pentamethylbicyclo[3.2.0]- and Bicyclo[2.2.1]heptadienyl Cations

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Recently several communications have dealt with the properties and rearrangements of polymethylbicyclo[3.2.1]octadienyl[1] and -[2.1.1]hexenyl[2] cations. In view of the intriguing interconversions within these ions we were interested to learn about the behavior of carbonium ions, which are intermediate between these types as far as the number of skeleton carbon atoms is concerned—seven instead of eight and six, respectively—viz., the polymethylbicyclo[3.2.0]- and -[2.2.1]heptadienyl cations. In the present publication the results of a study of the pentamethyl derivatives are reported.

Reduction of ketone **1**[3] with LiAlH$_4$ gave in good yield (77%) the crystalline secondary alcohol **2**. Upon ionization of **2** in