J. Am. Chem. Soc. **1989**, *111*, 1211–1216

Homogeneous Redox Catalysis Study of the Reductive Cyclization of 6-Hepten-2-one. Unusual Effects of the Nature and Concentration of the Catalyst

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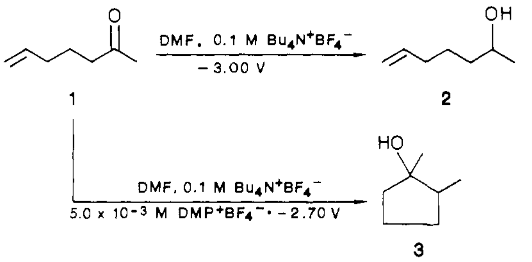
Abstract: Electrochemical reductive cyclization of 6-hepten-2-one can be effected by homogeneous redox catalysts. Effective catalysts include biphenyl, 2-methoxybiphenyl, naphthalene, and phenanthrene. The reaction consumed 2 F mol^{-1}, and *cis*- and *trans*-1,2-dimethylcyclopentanol were formed as exclusive products. The percentage of the cyclic alcohol that was cis increased with increasing redox catalyst concentration, increasingly positive reduction potentials of the catalyst, and increasing amounts of water present in the medium. These results are explained by invoking a mechanism involving reversible cyclization of the ketyl radical anion formed from reduction of 6-hepten-2-one. The cis or trans cyclized radical anions can be trapped by further reduction or by protonation to (ultimately) form the observed products.

The formation of tetraalkylammonium–mercury composites and their use in reductions of organic compounds has been recently explored.[2] In the absence of a substrate, cyclic voltammetry of a dimethylformamide (DMF) solution containing 0.10 M tetrabutylammonium fluoroborate ($Bu_4N^+BF_4^-$) and 5.0 × 10^{-3} M dimethylpyrrolidinium fluoroborate ($DMP^+BF_4^-$) exhibits a reversible wave at −2.70 V. Further investigations indicate that the reduction wave is due to the formation of an insoluble composite of DMP^+ and mercury of the composition $DMP(Hg_5)$.[3] DMP^+ has been demonstrated to catalyze the electroreduction of a variety of difficult to reduce substrates including aryl fluorides[4] and aliphatic ketones.[5] DMP^+-mediated reductions often lead to the formation of different products than reductions that are conducted in the absence of DMP^+. For instance, reduction of 6-hepten-2-one (**1**) at −3.00 V in DMF–0.1 M $Bu_4N^+BF_4^-$ gives 6-hepten-2-ol (**2**; eq 1). The presence of 5 × 10^{-3} M $DMP^+BF_4^-$ allows the reduction to occur at −2.70 V and results in the formation of a different product, 1,2-dimethylcyclopentanol (**3**; eq 2). Interestingly, the 1,2-dimethylcyclopentanol (**3**) formed is almost exclusively the isomer with the methyl groups cis. DMP^+-mediated electroreduction of several other unsaturated ketones also gives cyclized products (eq 3–5). Reductive cyclizations of **1** and other ketones have also been reported by Shono and co-workers to occur at Sn and graphite cathodes.[6]



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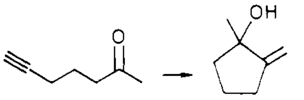

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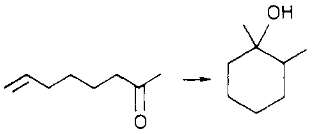

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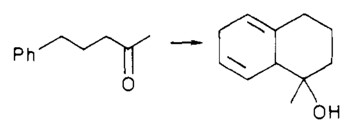

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We have investigated the mechanism of the DMP^+-mediated reductive cyclization of 6-hepten-2-one (Scheme I)[5] and found that it involves initial formation of $DMP(Hg_5)$ (step M1), which subsequently transfers an electron to the ketone forming the ketyl radical anion (step M2). The radical anion then cyclizes, forming a primary alkyl radical with an alkoxide substituent (step M3). That radical can then be further reduced (step M4) or a hydrogen atom from the solvent DMF (step M6) can be abstracted. Protonation of C^{2-} gives the observed 1,2-dimethylcyclopentanol (**3**). A key feature of the DMP^+-mediated reductions is that the catalyst $DMP(Hg_5)$ is a solid, which deposits at the cathode surface. In a simplistic way the catalytic system may be viewed as taking place at a $DMP(Hg_5)$ cathode rather that at an Hg cathode. We will refer to these processes as *heterogeneous redox catalysis*. This mechanism does not, however, offer an explanation as to why reduction in the presence of DMP^+ gives only cyclized product, while reduction in its absence gives only straight-chain alcohol, nor does it offer an explanation as to why the cyclization reaction occurs to give nearly exclusively cis product.

In order to investigate these problems further, we initiated a study of the reduction of 6-hepten-2-one (**1**) using homogeneous redox catalysis. Homogeneous redox catalysis techniques have been recently used to investigate a variety of reactions[7] and have provided information about rates and mechanisms of homogeneous

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(2) (a) Kariv-Miller, E.; Patcut, R.; Lehman, G. K. *Top. Curr. Chem.*, in press. (b) Kariv-Miller, E.; Andruzzi, R. *J. Electroanal. Chem., Interfacial Electrochem.* **1985**, *187*, 175.

(3) (a) Svetličić, V.; Kariv-Miller, E. *J. Electroanal. Chem., Interfacial Electrochem.* **1986**, *209*, 91. (b) Kariv-Miller, E.; Svetličić, V. *J. Electroanal. Chem., Interfacial Electrochem.* **1986**, *205*, 319. (c) Kariv-Miller, E.; Svetličić, V.; Lawin, P. B. *J. Chem. Soc., Faraday Trans. 1* **1987**, *23*, 1169. (d) Ryan, C. M.; Svetličić, V.; Kariv-Miller, E. *J. Electroanal. Chem., Interfacial Electrochem.* **1987**, *219*, 247.

(4) Kariv-Miller, E.; Vajtner, Z. *J. Org. Chem.* **1985**, *50*, 1394.

(5) (a) Kariv-Miller, E.; Mahachi, T. J. *J. Org. Chem.* **1986**, *51*, 1041. (b) Swartz, J. E.; Mahachi, T. J.; Kariv-Miller, E. *J. Am. Chem. Soc.* **1988**, *110*, 3622.

(6) Shono, T.; Mitani M. *J. Am. Chem. Soc.* **1971**, *93*, 5284. Shono, T.; Nishiguchi, I.; Ohmizu, H.; Mitani, M. *J. Am. Chem. Soc.* **1978**, *100*, 545. Shono, T.; Kise, N.; Suzumoto, T.; Marimoto, T. *J. Am. Chem. Soc.* **1986**, *108*, 4676.

(7) (a) Andrieux, C. P.; Savéant, J. M. In *Techniques of Chemistry*; Bernasioni, C. F., Ed.; Wiley: New York, 1986; Vol. VI, Chapter VII. (b) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savéant, J. M. *J. Electroanal. Chem., Interfacial Electrochem.* **1980**, *113*, 19. (c) Amatore, C.; Badoz-Lambling, J.; Bonnel-Huyghes, C.; Pinson, J.; Savéant, J. M. *J. Am. Chem. Soc.* **1982**, *104*, 1979. (d) Savéant, J. M. *Acc. Chem. Res.* **1980**, *13*, 323.

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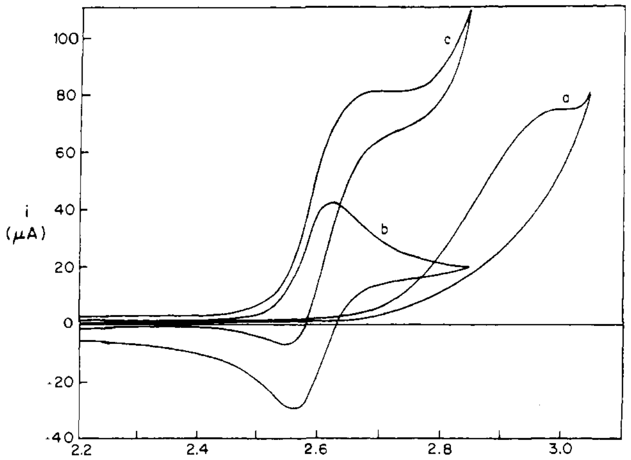
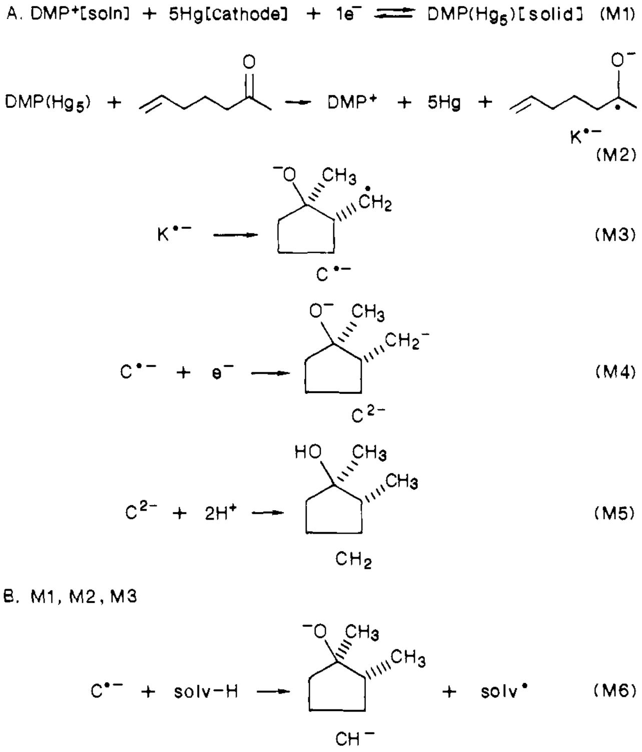


Figure 1. Cyclic voltammetry of biphenyl and 6-hepten-2-one (**1**): 0.10 M $Bu_4N^+BF_4^-$ in DMF, sessile hanging mercury drop electrode, 0 °C, 100 mV/s. (a) 1.0×10^{-2} M **1**; (b) 2.0×10^{-3} M biphenyl; (c) 2.0×10^{-3} M biphenyl + 1.0×10^{-2} M **1**.

Scheme I



reactions, which could not otherwise be obtained.[8] The use of redox catalysis can also change the pathway (as compared to direct electrode processes) of electrochemical processes.[9]

It was of interest to determine whether reductive cyclizations of unsaturated ketones could be induced by use of *homogeneous redox catalysis*. If successful, these experiments could contribute to the understanding of the role of $DMP(Hg_5)$ in the reductions mediated by DMP^+.

We present here a study of the reduction of 6-hepten-2-one (**1**) using homogeneous redox catalysts. The product yields and mechanism of the reaction will be discussed.

Table I. Reduction of 6-Hepten-2-one (**1**) and Biphenyl Redox Catalysis[a]

$[Ph_2]$, M × 10^3	initial current, mA	% **1**[b]	% **3**	cis/(cis + trans)[c]
0.5	8.3	42	41	0.783
2.0	30	51	48	0.800
2.0	24	51	48	0.802
5.0	32	52	44	0.836
20.0	40	51	42	0.855

[a] Electrolyses conducted on 1.0×10^{-2} M **1** in 25 mL of DMF at a stirred Hg cathode at −2.725 V vs SCE. A total of F mol^{-1} was passed. [b] Typical error was ±1%. [c] Typical error was ±0.003.

Table II. Biphenyl-Catalyzed Reduction of 6-Hepten-2-one (**1**) and Effect of the Amount of Charge Passed[a]

charge, F mol^{-1}	% **1**	% **3**	cis/(cis + trans)	current,[b] mA
0.25	87	11	0.93	6.4
0.50	74	22	0.90	5.0
0.75	65	36	0.87	4.0
1.00	53	49	0.82	3.2

[a] Electrolyses conducted on 1.0×10^{-2} M **1** in 25 mL of DMF at a stirred Hg cathode at −2.725 V vs SCE. $[Ph_2]$ = 0.5 mM. Cyclopentanol was added as an internal standard, and aliquots were withdrawn at indicated points, worked up, and analyzed by gas chromatography. [b] Current is the current at the time the sample was withdrawn.

Results

Studies were performed with a series of aromatic homgeneous redox catalysts in dry dimethylformamide containing 0.10 M $Bu_4N^+BF_4^-$. All potentials were measured and are reported with respect to a saturated calomel electrode, SCE. Cyclic voltammetry was conducted at a sessile hanging Hg drop electrode. Preparative electrolyses were conducted at a stirred Hg pool 0.15 V negative of the $E°$ of the redox catalyst and to the extent of passing 1 F mol^{-1} of ketone.

Biphenyl Catalysis. Cyclic voltammetry of 6-hepten-2-one (**1**) in DMF gave an irreversible wave near the solvent–electrolyte discharge (Figure 1a). Biphenyl exhibited a reversible wave at −2.65 V (Figure 1b). When biphenyl and 6-hepten-2-one (**1**) were mixed together, the cathodic peak current for biphenyl increased and the anodic peak current decreased (Figure 1c).

The ratio of peak current measured for a solution containing **1** and biphenyl to that measured for a solution of the same concentration of biphenyl alone increased with increasing [**1**]. This behavior indicates that biphenyl is an effective redox catalyst for the reduction of **1**.[7]

A preparative-scale electrolysis was conducted at −2.725 V on a solution of 2.0×10^{-3} M biphenyl and 1.0×10^{-2} M **1**. After passage of 1 F mol^{-1}, 48% of 1,2-dimethylcyclopentanol (**3**) was formed and 51% of **1** remained. It is worthwhile to note that attempts at electrolysis of **1** at this potential in the absence of biphenyl resulted in vanishingly small currents, which made preparative reduction impossible. Several observations with respect to this electrolysis are noteworthy. No 6-hepten-2-ol (**2**) or any other product was detected. The **3** formed was 80% cis and 20% trans with respect to the methyl groups. The initial current in the electrolysis was 30 mA, and it decayed to 20 mA after the passage of 1 F mol^{-1}. At the initial stages of the reduction, no color was observed in the reaction. After a few minutes a slight blue tinge could be observed on the surface of the mercury pool, and, in time, one could observe streaks of blue from the electrode surface out in to the bulk of the solution. Near the end of the electrolysis, the solution turned light blue. When the experiment was complete and the circuit was disconnected, the color faded within a few seconds.

Electrolysis of **1** in the presence of other concentrations of biphenyl proceeded similarly, giving comparable yields of **3** after passage of 1 F mol^{-1}. The currents in the electrolysis increased with increasing biphenyl concentration. In addition, the progression of solution coloration occurred more rapidly, and once

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[8] Andrieux, C. P.; Badoz-Lambling, J.; Combellas, C.; Lacombe, D.; Savéant, J. M.; Thiébault, A.; Zann, D. *J. Am. Chem. Soc.*, in press.

[9] (a) Swartz, J.; Stenzel, T. *J. Am. Chem. Soc.* **1984**, *106*, 2520. (b) Koppang, M. D.; Ross, G. A.; Woolsey, N. F.; Bartak, D. E. *J. Am. Chem. Soc.* **1986**, *108*, 1441.

Table III. Reduction of 6-Hepten-2-one (**1**) and Effect of Reduction Potential of the Catalyst[a]

catalyst	$E°$	% **1**	% **3**	cis/(cis + trans)
2-methoxybiphenyl	−2.690	46.4	50.0	0.753
biphenyl	−2.575	50.7	47.5	0.800
naphthalene	−2.495	57.7	40.2	0.825
phenanthrene	−2.424	48.1	34.5	0.874

[a] Electrolyses conducted on 1.0×10^{-2} M **1** in 25 mL of DMF at a stirred Hg cathode at 150 mV negative of $E°$. A total of 1 F mol^{-1} was passed. [catalyst] = 2.0×10^{-3} M.

the solution turned blue, it was more intensely colored at higher biphenyl concentrations. The percent of **3** that was cis also increased with increasing biphenyl concentration. Results are summarized in Table I. The results of the two experiments at 2.0×10^{-3} M biphenyl are presented to illustrate typical reproducibility of the data.

An experiment was conducted where the internal standard, cyclopentanol, was added to the cell prior to electrolysis, and periodically during the electrolyses samples were withdrawn, worked up (on a small scale), and analyzed by gas chromatography. Results are summarized in Table II. The amount of ketone decreased and amount of alcohol increased linearly as a function of the amount of charge passed. The slopes of such plots correspond to the consumption of 2 F mol^{-1}. The current and the percent of the alcohol that was cis decreased as the electrolysis progressed.

A 1 F mol^{-1} electrolysis conducted in DMF-d_7 in the presence of 5.0×10^{-3} M biphenyl resulted, after passage of 1 F mol^{-1} in the formation of a 48% yield of 1,2-dimethylcyclopentanol (**3**), which was 3 ± 2% monodeuteriated. The remaining alcohol was exclusively protio.

Other Catalysts. Electrolyses with naphthalene, phenanthrene, and 2-methoxybiphenyl were conducted in a fashion similar to those with biphenyl. Cyclic voltammetric results in the presence of these three catalysts were similar to results using biphenyl. The increase in reductive current for the catalyst peak upon addition of 6-hepten-2-one (**1**) occurs in the order 2-methoxybiphenyl > biphenyl > naphthalene > phenanthrene, following the order of the $E°$'s of the catalysts.

Preparative electrolysis experiments in the presence of any of the three catalysts resulted in the consumption of 2 F mol^{-1} of ketone reacted and in the quantitative formation of **3**. The percent of **3** that was cis varied significantly with the identity of the catalyst (Table III). In addition, the amount of color that appeared during the electrolyses varied with the catalyst. The 2.0×10^{-3} M naphthalene-mediated electrolysis gave coloration and product ratios similar to the 2.0×10^{-2} M biphenyl electrolysis. With 2.0×10^{-3} M phenanthrene the solution turned green as soon as the electrolysis began. The color intensified throughout the electrolysis, and it faded over a period of 10 min after the electrolysis was completed. With 2.0×10^{-2} M phenanthrene the percent of **3** that was cis increased to 0.92.

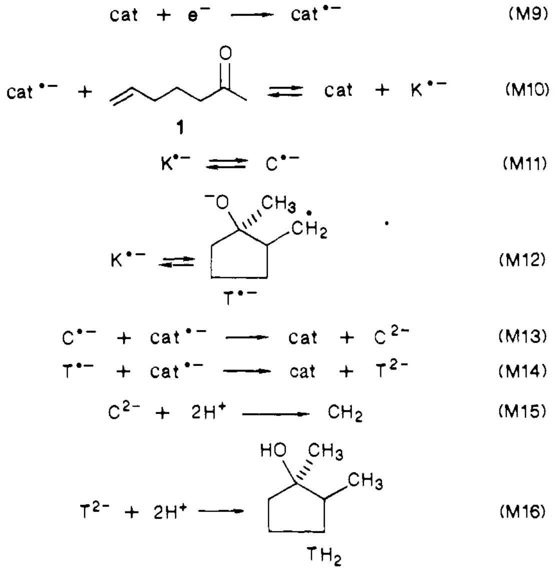
Effect of Added Water. In the early stages of this work we observed some variation in percentage of the cis isomer of **3** from batch to batch of solvent for a given set of reaction conditions. The trends of the effect of catalyst identity and concentration upon the product mixture were, however, entirely parallel from batch to batch of DMF. Since DMF is notorious for being difficult to dry,[10] we began to suspect that the variation in the product mixture could result from varying concentrations of residual water in the DMF. We undertook a more scrupulous drying procedure for DMF and a study of the effect of added water upon the product mixture. A series of electrolyses were conducted in the presence of 2.0×10^{-3} M biphenyl and varying amounts of water (Table IV). Only **3** was observed as a product in the range of [H_2O] studied. However, the percentage of the **3** that was cis increased as the amount of water increased. Almost no decrease in current efficiency was observed with addition of water, indicating little loss of reducing equivalents due to protonation of the catalyst radical anion or reduction of water.

Table IV. Biphenyl-Catalyzed Reduction of 6-Hepten-2-one (**1**) and Effect of Added Water[a]

[H_2O], M × 10^3	initial current, mA	% **1**	% **3**	cis/(cis + trans)
"0.0"	30	51	48	0.800
2.0	35	52	45	0.801
10.0	30	45	44	0.876
50.0	32	50	47	0.857
200	44	51	47	0.935
1000	35	49	49	0.965

[a] Reactions conducted in Burdick and Jackson DMF, which was distilled and stored over activated alumina; [6-hepten-2-one] = 1.0×10^{-2} M, [Ph_2] = 2.0×10^{-3} M at a stirred Hg pool. A total of 1 F mol^{-1} was passed at −2.725 V.

Scheme II



Discussion

Homogeneous redox catalysis is effective in the reduction of 6-hepten-2-one (**1**). Redox catalysts allow the reduction to be carried out several tenths of a volt positive of where reduction can be effected in their absence and directs the reduction *entirely* away from the formation of straight-chain alcohol. The reaction consumes 2 F mol^{-1} of ketone reacted and forms a cyclic product, quantitatively. These effects are similar to those observed for DMP$^+$ catalysis of the reduction of **1**.[5]

Unlike the results from DMP$^+$ catalysis, the stereochemistry of the cyclic product that is formed varies with the design of the experiment. Under most conditions, mixtures of *cis*- and *trans*-1,2-dimethylcyclopentanol (**3**) are formed with the percent cis being significantly lower than in the case of DMP$^+$ catalysis. The percent of the 1,2-dimethylcyclopentanol that is cis depends upon the identity of the redox catalyst, its concentration, and the amount of water present in the electrolysis medium.

In Scheme II we present a mechanism that can account for these unusual effects of catalyst concentration and identity and amount of water present. The proposed mechanism is very similar to that proposed for DMP$^+$-mediated reductive cyclization of **1** (Scheme I). The major difference between the two mechanisms is the reversibility of the cyclization steps. We will now discuss that mechanism in terms of our homogeneous catalysis experiments.

Steps M9 and M10 are obviated by the fact that the current for the catalyst in cyclic voltammetry increased as **1** was added and by the fact that preparative electrolyses could be effected at more positive potentials in the presence of the catalyst than in

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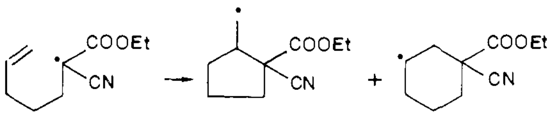
[10] (a) de la Torre, R. A.; Sease, J. W. *J. Am. Chem. Soc.* **1979**, *101*, 1687. (b) La Perriere, D. M.; Willelt, B. C.; Carroll, W. F., Jr.; Torp, E. C; Peters, D. G. *J. Am. Chem. Soc.* **1978**, *100*, 6293. (c) Peters, D. G., private communication.

its absence. The mechanism of the cyclization must be somewhat more elaborate than Scheme I to allow for the variation in the relative amounts of the two stereoisomers with the identity and concentration of the catalyst.

The variation in the amount of product formed with reaction conditions is reminiscent of a reaction in which both kinetic and thermodynamic control are exerted. We propose that the cyclization of the ketyl radical anion, $K^{\bullet-}$, in steps M11 and M12 is reversible. Cyclization to form $C^{\bullet-}$, step M11, is likely to occur more rapidly than cyclization to form $T^{\bullet-}$, step M12.[5b,11] Steps M13 and M14 involve the reduction of a primary alkyl radical, a species whose reduction potential is expected to be nearly 1 V positive of the potentials for the redox catalysts used.[12] Thus, we expect the rates of steps M13 and M14 to be near the diffusion-controlled limit.[13] When the concentration of the redox catalyst is higher, the current is higher, more $cat^{\bullet-}$ is produced, and the rates of M13 and M14 will be higher. At high catalyst concentration, the kinetic product, $C^{\bullet-}$, is trapped and the formation of *cis*-1,2-dimethylcyclopentanol predominates.

Since $K^{\bullet-}$ is also present and is a strong reducing agent, it may serve instead of $cat^{\bullet-}$ in steps M13 and M14. The data available to us do not allow us to distinguish whether $cat^{\bullet-}$, $K^{\bullet-}$, or both act as the reducing agent in steps M13 and M14.

Although it is believed that cyclization of simple unsaturated alkyl radicals is not reversible,[14] reversibility of the cyclization of some resonance-stabilized radicals has been proposed to rationalize the nature of products formed.[15] Julia and co-workers have studied the cyclization shown in eq 6 and found more five-membered ring product when good hydrogen atom donors were present. They explained their results by invoking a reversible cyclization and trapping the kinetic product by hydrogen atom abstraction. Although the reactions that trap $C^{\bullet-}$ or $T^{\bullet-}$ in our system are different than those of Julia, the arguments offered by Julia for reversible cyclization are similar to ours.



(6)

The fact that 2-propanoate ion is a much better hydrogen atom donor (the hydrogen attached to C-2 being removed) than 2-propanol, a normal methylene, or methyne group[16] leads us to believe that the carbon–hydrogen bond of an alcoholate is substantially weaker than a "normal" C–H bond. The new carbon–carbon bonds in $C^{\bullet-}$ and $T^{\bullet-}$ may also be weaker, and this may allow for reversibility of the cyclization similar to that observed by Julia.

A similar explanation can be offered for the effect of the identity of the redox catalyst upon the stereochemical composition of the products. The electrolyses were conducted 150 mV positive of the $E°$ for the catalysts, and the catalysts were, thus, reduced at a virtually identical, diffusion-controlled rate. The more positive the $E°$ of the catalyst, the slower step M10,[7] the more the catalyst radical anion will build up during electrolysis, and, accordingly, the percentage of the cis stereoisomer in the product mixture will be higher. This association is supported by the decrease in the amount of catalysis observed in cyclic voltammetry and by the longer time the color persisted after the end of the electrolyses as the reduction potential of the catalyst became more positive. The buildup of the catalyst radical ion is, in fact, observed in the coloration of the electrolysis solutions.

The mechanism outlined in Scheme II also allows for explanation of the variation in the percent of cis product with the amount of charge passed in the reaction. At early stages of the reaction the current and [K] are high. Since [K] is high, the rate of step M10 will also be high and $K^{\bullet-}$ will be formed in a zone close to the electrode, which contains a high concentration of reducing agents ($cat^{\bullet-}$, $K^{\bullet-}$). When cyclization (steps M11 and M12) occurs, the $C^{\bullet-}$ and $T^{\bullet-}$ are rapidly trapped by the reducing agents (steps M13 and M14). As the reaction progresses, the [K] and the current decrease. Reaction M10 is slower, and $cat^{\bullet-}$ diffuses further from the cathode before reducing K. Cyclization forms $C^{\bullet-}$ and $T^{\bullet-}$ are more distant from the cathode in region where reducing-agent concentrations are lower. Thus, M13 and M14 are slower, and $C^{\bullet-}$ and $T^{\bullet-}$ have a chance to equilibrate, giving a lower percent of cis in the final reaction mixture. It is important to recognize that the current at the beginning of the electrolysis is 7.5 times that for 5×10^{-4} M biphenyl alone; thus, most of the current is a catalytic current. Since the $cat^{\bullet-}$ is oxidized by the K and does not build up in solution, the decrease in current as the electrolysis proceeds is not primarily due to a decrease in the bulk [cat] but a decrease in [K], which slows step M10 and decreases the catalytic current. The concentration profiles in these reactions are complex and are dependent upon the rates of steps M10–M12 as well as the rate of stirring and the electrode potential. A similar effect of the current upon the reaction products was observed by Lund and co-workers in the electrodimerization of benzylidenemalononitrile.[17]

Cyclic voltammetric studies[18] using homogeneous redox catalysis techniques[7] indicate that the rate-limiting step under the conditions of experiments, with the exception of the 2-methoxybiphenyl mediated electrolysis, is step M10. Since cyclization occurs after the rate-limiting step, no kinetic information can be obtained about its rate and/or reversibility. It should be noted that, even though step M10 is the rate-limiting step, it is reasonable that the relative rates of steps M11–M14 may determine the mixture of products. In the case of 2-methoxybiphenyl, step M10 no longer determines the rate of the reaction. The working curves of Savéant and co-workers do not allow us to determine the rates of steps M11 and M12 when they are reversible, but work is currently under way to analyze the data in a way to reveal those rates.

It is worthwhile to note that the percent of cis formed after 1 F mol^{-1} was passed in the reaction where aliquots were withdrawn is substantially higher than that in the reaction noted in Table I (0.82 vs 0.78). An important difference between these reactions is that, in the reaction where aliquots were withdrawn, the gas chromatographic standard, cyclopentanol, was added prior to electrolysis, where in the reaction cited in Table I the cyclopentanol was not added until after completion of the electrolysis. We believe that cyclopentanol acts as a proton donor, as does water, an effect that will be discussed below.

An alternative explanation for the change in the percent of cis product as the reaction progresses is that the reaction mixture gets progressively more basic as the reaction progresses and protonation (as described in the next section) has a smaller effect.

The lack of any deuterium incorporation in the products when the reduction was conducted in DMF-d_7 indicates that a step involving hydrogen atom abstraction from the solvent does not operate to any extent. There is ample evidence that the solvent is the best hydrogen atom donor in the reaction mixture.[19]

Water also had a dramatic effect upon the progress of the reaction. The percentage of **3** that was cis increased with increasing [H_2O]. Results similar to these have been observed for reduction of **1** at Pb electrodes in the presence of H_2O.[20] We can elaborate our mechanisn as described in Scheme III to account for this fact. $C^{\bullet-}$ and $T^{\bullet-}$ can be trapped by protonation in steps M17 and M18 in addition to being trapped by reduction. $C^{\bullet-}$ and

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(11) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron* **1985**, *41*, 3925. Spellmeyer, D. C.; Houk, K. N. *J. Org. Chem.* **1987**, *52*, 959.

(12) Andrieux, C. P.; Gallardo, I.; Savéant, J. M.; Su, K. B. *J. Am. Chem. Soc.* **1986**, *108*, 638, and private communication.

(13) Dorfman, L. M. *Acc. Chem. Res.* **1970**, *3*, 224.

(14) Wilt, J. W. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vo. 1, Chapter 8, pp 418–448.

(15) Julia, M.; Maumy, M.; Mion, L. *Bull. Soc. Chim. Fr.* **1967**, 2641.

(16) Swartz, J. E.; Apel, E. A.; Kosek, P. S. 190th National Meeting, of the American Chemical Society, Chicago, IL, Sept 1985; American Chemical Society: Washington, DC, 1985; Abstract ORGN 127, and unpublished work. Andrieux, C. P.; Badoz-Lambling, J.; Combellas, C.; Lacombe, D.; Savéant, J. M.; Thiébault, A.; Zann, D. *J. Am. Chem. Soc.* **1987**, *109*, 1518.

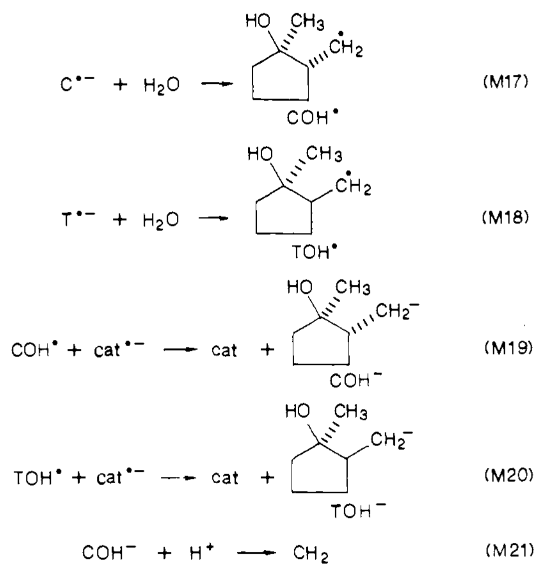
(17) Pedersen, S. U.; Hazell, R. G.; Lund, H. *Acta Chem. Scand., Ser. B* **1987**, *41*, 336.

(18) Swartz, J. E.; Zion, D. A., to be submitted for publication.

(19) Swartz, J. E.; Kosek, P. J.; Apel, E. A.; Marr, K., unpublished work.

(20) Lawin, P. B.; Hutson, A.; Kariv-Miller, E., unpublished work.

Scheme III



$T^{\bullet-}$ are tertiary alcoholates and their protonation by water should be rapid[21] as it is a thermodynamically favored proton transfer[22] from an oxygen acid to an oxygen base. Protonation traps the more rapidly formed $C^{\bullet-}$, much as reducing it does, and, therefore, increasing the water content of the solvents favors the kinetic, cis, product. The small effect of 2×10^{-3} M added water, which can be considered negligible, is likely to reflect the residual moisture level in our medium. It is reasonable that solvent and electrolyte from our sources handled in the way we did contains ca. 5×10^{-3} M residual water.[10c]

Comparison of Heterogeneous and Homogeneous Catalysis. It is worthwhile, at this point to make a comparison of the mechanism and stereochemistry of reductive cyclization of 6-hepten-2-one (**1**) mediated by homogeneous redox catalysts and by DMP^+.[5] DMP^+, a heterogeneous redox catalyst, and the aromatic hydrocarbon homogeneous redox catalysts used in this study have similar reduction potentials. The $E°'$ for reduction of DMP^+ at Hg is −2.57 V vs SCE,[3d] almost identical with that of biphenyl. Both heterogeneous and homogeneous catalysts lead to the reductive cyclization of **1** to form **3**. In all cases the major isomer of **3** is the cis isomer.

Some differences between DMP^+ and aromatic hydrocarbon catalysis are also apparent. The catalysis as measured by cyclic voltammetry (peak current for the catalyst plus **1** divided by peak current for the catalyst alone) for DMP^+ is nearly independent of $[DMP^+]$,[5b] but in the case of biphenyl catalysis is dependent upon [biphenyl]. The DMP^+-catalyzed reductions give a higher fraction, 0.85–0.95, of the cis isomer of **3** than reactions catalyzed by biphenyl. In the case of DMP^+ catalysis the fraction of **3** that is cis is independent of $[H_2O]$, while in the case of biphenyl mediation the fraction of cis increases with increasing $[H_2O]$. The DMP^+-mediated reactions include a pathway (Scheme I, pathway B) that involves, to a significant extent, abstraction of a hydrogen atom from the solvent. The homogeneous catalyzed reactions do not.

We believe that these differences can be accounted for by the nature of the mediation. DMP^+ mediation involves the reaction of the ketone with solid $DMP(Hg_5)$ at the electrode surface, where homogeneous redox catalysis involves reaction of the ketone with the soluble catalyst radical anion, which is not localized at the electrode surface. The rate of step M2 is, thus, dependent upon the surface area of the $DMP(Hg_5)$ and nearly independent of the $[DMP^+]$. In homogeneous catalysis the rate of the analogous reaction, step M10, is dependent upon the catalyst concentration. These facts offer an explanation for the different behavior in cyclic voltammetry of heterogeneous and homogeneous catalysts.

Similarly, the differences in the nature of the catalyst can explain the differences in the fraction of cis-**3**, which is formed. In the case of DMP^+ mediation, the ketyl radical anion is formed at the surface of the $DMP(Hg_5)$. If $K^{\bullet-}$ cyclizes before escaping from the surface of the $DMP(Hg_5)$, the product, $C^{\bullet-}$ or $T^{\bullet-}$, will be immediately reduced by the $DMP(Hg_5)$. The kinetic product, $C^{\bullet-}$, is, thus, trapped, and *cis*-1,2-dimethylcyclopentanol is formed as the major product.

In the case of DMP^+ mediation, if the radical anion escapes from the electrode surface, it cannot be further reduced (since no reducing agent is present in solution), and it eventually either returns to the electrode surface or abstracts a hydrogen atom from the solvent.[5b] In the case of homogeneous catalysis, $C^{\bullet-}$ and $T^{\bullet-}$ are formed in a dilute solution of catalyst radical anion and, as we have described, the amount of kinetic product trapped depends upon the concentration of the catalyst radical anion. From results in DMF-d_7 it is apparent that steps M13 and M14 are more rapid than hydrogen atom abstraction (step M6) under the conditions of that experiment.

Water does not effect the amount of **3** that is cis in the DMP^+-mediated reductions, but is has a dramatic effect on the homogeneously catalyzed reductions. An explanation for this is that, in the DMP^+-mediated reductions, much of the cyclization occurs near the $DMP(Hg_5)$ surface, and the resulting cyclic radical, $T^{\bullet-}$ or $C^{\bullet-}$, is rapidly reduced (before protonation can occur). In the homogeneous redox catalysis experiments, cyclization occurs in the bulk solution and $K^{\bullet-}$ or $T^{\bullet-}$ can either be reduced by $cat^{\bullet-}$ or $K^{\bullet-}$ (step M13 or M14) or be protonated by H_2O (step M17 or M18). (Both reactions, M13 or 14 and M17 or 18, should occur near the diffusion-controlled limit.) Whether trapping by $cat^{\bullet-}$ or H_2O occurs will depend only upon the relative concentrations of those species. In addition, in the case of DMP^+ catalysis, the proportion of **3** that is cis is so high in dry solvent that it would be more difficult to observe an increase in that proportion brought upon by added H_2O.

We now consider the question as to why reduction in the absence of a mediator (either DMP^+ or a homogeneous catalyst) gives only straight-chain alcohol while reduction in the presence of a mediator gives only a cyclic alcohol. We know that the initial product of electron transfer, $K^{\bullet-}$, once formed, can cyclize. In the case of nonmediated reduction, something must intercept $K^{\bullet-}$ prior to cyclization. There are no differences between direct and mediated reductions except the presence of the mediator and the potential of the reduction. Since the mediators are divergent in structure (aromatic hydrocarbons and a tetraalkylammonium ion). We do not believe it is likely that they, in and of themselves, are responsible for redirecting the reduction. We are left then with the potential as the only difference between direct and mediated reductions, which could cause the difference in products formed. Mediated reductions are carried out with effective reduction potentials substantially positive (0.3–0.5 V) of in their absence. $K^{\bullet-}$ may have a reduction potential more negative than −2.75 V but more positive than −3.1 V. It could then be intercepted, prior to cyclization, in direct reductions by reduction to the dianion, which does not cyclize but is protonated to form the straight-chain alcohol.

Conclusions

Reduction of 6-hepten-2-one (**1**) can be effected by the use of homogeneous redox catalysts. The use of such catalysts allows reduction to occur 0.3–0.40 positive in their absence, consumes 2 F mol^{-1}, and redirects the products of reduction from simple reduction of the ketone to alcohol to a reductive cyclization. The 1,2-dimethylcyclopentanol (**3**) formed is mostly cis, and the percent of cis depends upon the reduction potential of the catalyst, the concentration of catalyst, and the amount of water present in the reaction mixture. These variations can be explained by a mechanism involving reduction of the catalyst followed by transfer

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(21) Eigen, M. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 1.

(22) Olmstead, W. N.; Margolin, Z.; Bordwell, F. G. *J. Org. Chem.* **1980**, *45*, 3295. Burrette, W. C.; Johnson, H. W., Jr.; Sawyer, D. T. *Anal. Chem.* **1984**, *56*, 1890.

(23) House, H. O.; Feng, E.; Peet, N. P. *J. Org. Chem.* **1971**, *36*, 2371.

of an electron from the reduced catalyst to the ketone (forming the ketyl). The ketyl then cyclizes, reversibly, to form a cyclic radical anion, which is trapped either by further reduction or protonation. The conditions that dictate the rate of the trapping reactions alter the proportion of kinetic (cis) and thermodynamic (trans) products. The differences between DMP^+ and aromatic hydrocarbon mediated reductions can be explained by the fact that, in the former case, mediation is by an insoluble, heterogeneous catalyst and, in the latter case, by a homogeneous catalyst.

Experimental Section

Apparatus. A 3-compartment cell[5] was used for all experiments. Princeton Applied Research Models 173, 175, and 179 were used for potentiostatic control and coulometry. A mercury pool (9 cm^2) was used as the cathode for preparative experiments, and a sessile hanging mercury drop[2b] was used for cyclic voltammetry. A platinum flag electrode (4 cm^2) served as the anode, and a sodium-saturated calomel electrode in contact with the solution through agar and methyl cellulose bridges was used as the reference electrode. Gas chromatography was conducted on a Varian 3740 gas chromatograph equipped with a 20-m Carbowax coated fused silica column and a flame ionization detector. Standard methods using cyclopentanol as an internal standard were employed. Routine mass spectral analysis was conducted on a Hewlett Packard 5992 GC–MS system using a 30-m SE54 fused silica column. Deuterium-labeling analysis was conducted on a VG 7070E-HF operating at an ionizing voltage of 20 eV in the selected ion recording mode. Reaction components were separated on a Hewlett Packard 5890 gas chromatograph equipped with a J and W Scientific 30-m DB-5 capillary column eluting directly into the VG 7070E source. Polarography was conducted at 0 °C in 0.1 M $Bu_4N^+BF_4^-$ in DMF with a PAR 174 polarograph using sampled DC techniques at a 0.5-s drop time. For all catalysts the limiting current was linear with [catalyst], and the $E_{1/2}$ was invariant with concentration.

Materials. DMF was purchased from Burdick and Jackson, vacuum distilled, retaining the middle 60%, and stored over activated alumina. DMF-d_7 (99% D) was purchased from Aldrich and purified as above. $Bu_4N^+BF_4^-$ was prepared by reaction of $Bu_4N^+Br^-$ with HBF_4[22] and recrystallized two or three times from ethyl acetate–pentane. For data given in any table, one batch of 0.10 M $Bu_4N^+BF_4^-$ in DMF was prepared, stored overnight over activated alumina, and transferred via syringe to a one-neck flask containing activated alumina and equipped with a three-way stopcock. The solvent was withdrawn with a syringe through the stopcock while dried N_2 flowed through the other arm of the stopcock. 6-Hepten-2-one was prepared as previously described.[5a] The cathode material was Bethlehem triple-distilled mercury. Biphenyl, 2-methoxybiphenyl, naphthalene, and phenanthrene were purchased in the highest purity available from Aldrich and used without further purification.

Electrolysis (Typical). The electrochemical cell was removed from the oven and cooled while flushing with dried argon. Mercury (7 mL) was added, and a small stir bar and electrodes were installed. DMF and 0.1 M $Bu_4N^+BF_4$ were added to the cathode (25 mL) and anode (7 mL) compartments. The cell was placed in an ice bath, the catholyte was purged with argon for 5 min, and the solution was preelectrolyzed at −2.750 V until the current decayed to a small, constant value. The coulometer was set to compensate for the residual current (typically ca. 2 mA) at −2.725 V. Biphenyl (7.7 mg, 5×10^{-5} mol) was added, the solution stirred, and a cyclic voltammogram recorded at a sweep of 100 mV s^{-1}. 6-Hepten-2-one, (28 mg, 2.5×10^{-4} mol) was added, and the solution was stirred and then electrolyzed at −2.725 V until 24 C (1 F mol^{-1} of ketone) had passed. The color was allowed to dissipate, and acetic acid (2 mL, 0.1 M) and cyclopentanol (2.5×10^{-4} mol in 200 μL of DMF) were added.

The catholyte and mercury were poured into a separatory funnel containing 75 mL of saturated aqueous NaCl, the cell was washed with 25 mL of ether, and the ether was added to the separatory funnel. The funnel was shaken, the Hg layer was drained off, and the aqueous and ether layers were separated. The aqueous phase was extracted two additional times with ether (25 mL), the combined ether phases were washed with saturated sodium chloride (3 × 25 mL), and the ether phase was dried with $MgSO_4$.

Products were identified by comparison of GC and GC–MS behavior with authentic compounds. Product yields were determined by gas chromatography.

Acknowledgment. We are grateful to the National Science Foundation for support of this work and to a Northwest Area Foundation grant from the Research Corp. and Grinnell College for partial support of J.E.S. during a leave from Grinnell College. We also thank Dr. Edmund Larka for his assistance in obtaining mass spectral data in order to assay deuterium incorporation in the labeling experiments.

Registry No. DMF, 68-12-2; $Bu_4N^+BF_4^-$, 429-42-5; Hg, 7439-97-6; water, 7732-18-5; 6-hepten-2-one, 21889-88-3; biphenyl, 92-52-4; 2-methoxybiphenyl, 86-26-0; naphthalene, 91-20-3; phenanthrene, 85-01-8; *cis*-1,2-dimethylcyclopentanol, 16467-04-2; *trans*-1,2-dimethylcyclopentanol, 16467-13-3.