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Electroreductive Intramolecular Cyclization of a Bromo Propargyloxy Ester Catalyzed by Nickel(I) Tetramethylcyclam Electrogenerated at Carbon Cathodes in Dimethylformamide

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Cyclic voltammetry and controlled-potential electrolysis have been employed to investigate and characterize the reductive intramolecular cyclization of ethyl 2-bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (**1**) promoted by (1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane)nickel(I), $[Ni(tmc)]^+$, electrogenerated at glassy carbon cathodes in dimethylformamide containing tetraalkylammonium salts. Cyclic voltammograms for reduction of $[Ni(tmc)]^{2+}$ in the presence of **1** reveal that $[Ni(tmc)]^+$ catalytically reduces **1** at potentials more positive than those required for direct reduction of **1**. During controlled-potential electrolyses of solutions containing $[Ni(tmc)]^{2+}$ and **1**, catalytic reduction of the latter proceeds via one-electron cleavage of the carbon−bromine bond to form a radical intermediate that undergoes cyclization to afford 2-(3′,4′-dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methylenetetrahydrofuran (**2**). In the presence of a base (either electrogenerated or deliberately added as potassium *tert*-butoxide), **2** rearranges to give 2-(3′,4′-dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methyl-2,5-dihydrofuran (**3**). A mechanistic scheme is proposed to explain the results obtained by means of cyclic voltammetry and controlled-potential electrolysis.

Introduction

Owing to their widespread presence in nature as well as their breadth of biological activity, lignans have attracted considerable attention from organic chemists.[1] Some lignans exhibit antitumor activity, whereas others function as diuretic, analgesic, and antirheumatic compounds. A major subgroup of lignans is the family of furofuran lignans, the synthesis of which poses interesting and often unsolved problems of stereocontrol. Although several synthetic approaches have been reported, radical cyclization continues to be a central methodology for the preparation of natural products containing heterocyclic rings.[2,3] Radical cyclization procedures have several advantages over other methods that require laborious multistep alternative synthesis. A majority of radical cyclizations in heterocyclic chemistry are still accomplished with the aid of tri-*n*-butyltin hydride, Bu_3SnH;[3−5] such syntheses typically involve the use of an excess of Bu_3SnH in the presence of a small amount of radical initiator, usually azobisisobutyronitrile (AIBN). For example, a highly stereocontrolled total synthesis of a furofuran lignan, isogmelinol,[6] has been accomplished by means of this approach; a key step in this synthesis is the intramolecular radical cyclization of ethyl 2-bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (**1**) to form 2-(3′,4′-dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methylenetetrahydrofuran (**2**).

To avoid the use of toxic triorganotin hydrides, which are also troublesome to separate from the desired products, considerable effort has been aimed at development of new methodologies for the generation of reactive radicals. In lieu of Bu_3SnH, tri-*n*-butylgermanium hydride (Bu_3GeH) has been employed by Dolbier and coworkers.[7] Although quite expensive, Bu_3GeH is much less toxic and reacts only slightly less rapidly than Bu_3SnH in promoting reductive intramolecular cyclizations. Another reductant, tris(trimethylsilyl)silane [$(Me_3Si)_3SiH$], is less toxic and easier to remove via conventional workup procedures than Bu_3SnH, but is more costly.[8] It has also been demonstrated that 1-ethylpiperidinium hypophosphite (a low-cost reagent) and AIBN can be used to effect the intramolecular radical cyclizations of alkyl bromide

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substrates with alkene side chains[9] and of acetylenic bromides.[10] A significant advance for processes involving radicals has been the use of solid-phase methodology.[11,12] Major advantages of solid-phase syntheses are that the radical precursor is attached to a resin and that the tin reagent used in the reaction can be removed by simple washing after the radical cyclization is complete; thus, the desired product can easily be obtained in a pure form.

A convenient alternative to synthetic methods involving organometallic hydrides is the use of electrogenerated nickel(I) complexes as mediators for reductive intramolecular cyclizations.[13−19] Ozaki and co-workers[13] have shown that the generation of alkyl and vinyl radicals from various organic halides by nickel(I) species, acting as electron-transfer catalysts, can lead to the formation of carbocyclic products in good yield at room temperature. In an investigation of radical cyclization reactions promoted by electrogenerated nickel(I) complexes, Ihara et al.[14] demonstrated that tetrahydropyrans can be obtained from bromoacetals possessing electron-deficient olefinic moieties. Nickel(I) complexes, electrogenerated under constant-current conditions, have been employed by Olivero et al.[15] to catalyze the intramolecular cyclization of 2-haloaryl ethers containing unsaturated side chains; these workers reported that the nature of the organonickel catalyst (in particular, the identity of the ligand) strongly affects the speed, selectivity, and mechanism of the electrochemical process. Reductive intramolecular cyclization of 6-iodo- and 6-bromo-1-phenyl-1-hexyne, catalyzed by electrogenerated nickel(I) salen, leads to the production of benzylidenecyclopentane in 84−95% yield.[16] More recently, the nickel(I) salen-catalyzed reduction of 6-bromo-1-hexene has been shown to entail cleavage of the carbon−bromine bond to give the 5-hexen-1-yl radical, which undergoes intramolecular cyclization to form methylcyclopentane as well as dimeric species arising from coupling of both cyclic and acyclic radicals.[17] Esteves et al.[18,19] reported that electrogenerated nickel(I) complexes catalyze the intramolecular cyclization of unsaturated halides to yield alkenyl radicals that can react intramolecularly to give carbocyclic products. Pletcher and co-workers[20−24] have shown that radical intermediates are also involved in a number of nickel(I)-catalyzed reductions of alkyl monohalides.

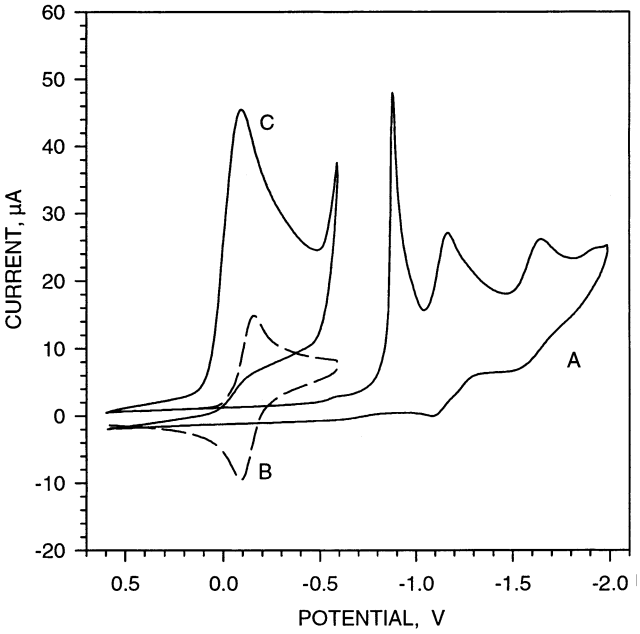
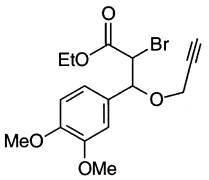


FIGURE 1. Cyclic voltammograms recorded with a glassy carbon electrode (area = 0.077 cm^2) at 100 mV s^{-1} in DMF containing 0.10 M $TEABF_4$ and (A) 1.00 mM **1**, (B) 1.00 mM $[Ni(tmc)]Br_2$, and (C) 1.00 mM $[Ni(tmc)]Br_2$ and 5.00 mM **1**.

In this paper, we report electrochemical and mechanistic results obtained in a study of the reductive intramolecular cyclization of ethyl 2-bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (**1**) that is catalyzed



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by electrogenerated (1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane)nickel(I), $[Ni(tmc)]^+$. Experimental parameters, including the initial ratio of parent nickel(II) complex to **1**, the identity of the supporting electrolyte, and the presence of an added proton donor (1,1,1,-3,3,3-hexafluoro-2-propanol), have been examined to ascertain how these variables affect the yield and identity of cyclic products.

Results and Discussion

Cyclic Voltammetric Behavior of Ethyl 2-Bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (1). Shown in Figure 1, curve A, is a cyclic voltammogram recorded at a scan rate of 100 mV s^{-1} for the direct reduction of a 1.00 mM solution of **1** at a glassy carbon electrode in DMF containing 0.10 M $TEABF_4$. We

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attribute the sharp peak at −0.82 V to irreversible two-electron reductive cleavage of the carbon−bromine bond, giving rise to an alkene, the reduction of which exhibits three cathodic waves at more negative potentials. In a subsequent paper, we will provide a detailed analysis of the cyclic voltammograms, along with product distributions and mechanistic steps, for the direct reduction of **1**.

Cyclic Voltammetric Behavior of (1,4,8,11-Tetramethyl-1,4,8,11-tetraazacyclotetradecane)nickel(II) Bromide, [Ni(tmc)]Br$_2$. Cyclic voltammograms were recorded with a glassy carbon electrode at scan rates (v) ranging from 20 to 200 mV s^{-1} for solutions of [Ni(tmc)]Br$_2$ in DMF containing 0.10 M TEABF$_4$. A cyclic voltammogram obtained at a scan rate of 100 mV s^{-1} is depicted in Figure 1, curve B. We found that the separation of cathodic and anodic peak potentials ($\Delta E_p = E_{pc} - E_{pa}$) is close to 60 mV, that the ratio of peak currents (I_{pc}/I_{pa}) is unity, and that $I_{pc}/v^{1/2}$ is independent of scan rate. Thus, [Ni(tmc)]$^{2+}$ undergoes a reversible one-electron reduction to the stable [Ni(tmc)]$^+$ species, and the formal potential for this process is −0.15 V; moreover, no other reduction occurs within the potential range of the medium. Most importantly, [Ni(tmc)]$^{2+}$ is reduced at potentials where neither **1** nor any product derived from **1** is electroactive.

Similar results were obtained in cyclic voltammetric studies of solutions of [Ni(tmc)]Br$_2$ in DMF containing either 0.10 M TBABF$_4$ or 0.10 M TMABF$_4$. In each of these two media, the formal potential for the [Ni(tmc)]$^{2+}$−[Ni(tmc)]$^+$ redox couple is −0.12 V.

We performed controlled-potential electrolyses of solutions of [Ni(tmc)]Br$_2$ at potentials just negative of the reduction peak, and the coulometric n value was 1. Accordingly, all voltammetric and coulometric data indicate that the electrode process is

$$[\mathrm{Ni(tmc)}]^{2+} + e^- \rightleftharpoons [\mathrm{Ni(tmc)}]^+$$

These results are in agreement with extensive data collected by Pletcher and co-workers[20,23] concerning the behavior of [Ni(tmc)]$^{2+}$ at platinum electrodes in acetonitrile.

Cyclic Voltammetric Behavior of [Ni(tmc)]Br$_2$ in the Presence of Ethyl 2-Bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (1). When **1** is added to a solution of [Ni(tmc)]Br$_2$, the cyclic voltammetric behavior of the nickel(II) complex changes dramatically. Figure 1, curve C, shows a cyclic voltammogram recorded with a glassy carbon electrode at a scan rate of 100 mV s^{-1} for a solution consisting of 5.00 mM **1** and 1.00 mM [Ni(tmc)]Br$_2$ in DMF containing 0.10 M TEABF$_4$. In comparison with curve B, the cathodic current corresponding to reduction of [Ni(tmc)]$^{2+}$ to [Ni(tmc)]$^+$ is much higher in curve C, whereas the anodic peak disappears because electrogenerated [Ni(tmc)]$^+$ is consumed during the catalytic reduction of **1**. On further addition of **1**, the cathodic current increases further, although the increase is not proportional to the concentration of **1** over a large concentration range. Furthermore, with progressive increases in the concentration of **1**, the cathodic peak potential shifts toward more negative values. Similar behavior is observed when these experiments are repeated in DMF containing 0.10 M TBABF$_4$. Table 1 is a compilation of data obtained from experiments carried out in DMF containing 0.10 M TEABF$_4$, where $(I_{pc})_c$ is the cathodic peak current in the presence of **1** and $(I_{pc})_d$ is the cathodic peak current in the absence of **1**. These results suggest that, on the time scale of cyclic voltammetry, the reaction between **1** and electrogenerated [Ni(tmc)]$^+$ is fast (because the anodic peak for oxidation of [Ni(tmc)]$^+$ is absent) but that the original [Ni(tmc)]$^{2+}$ species is regenerated sluggishly, since the increase in $(I_{pc})_c$ is a measure of the rate at which [Ni(tmc)]$^{2+}$ is regenerated. On the basis of the results in Table 1, it can be concluded that the extent of the catalytic reaction increases with increasing concentration of **1** for a given mediator concentration.

TABLE 1. Peak-Current Ratios Obtained from Cyclic Voltammograms of Solutions of DMF Containing 0.10 M TEABF$_4$, 1 mM [Ni(tmc)]$^{2+}$, and Various Concentrations of 1 at 100 mV s^{-1}

	1 mM	2 mM	5 mM	10 mM
$(I_{pc})_c/(I_{pc})_d$[a]	2.26	3.14	3.74	4.20

[a] $(I_{pc})_c$ = catalytic peak current in the presence of **1** and $(I_{pc})_d$ = diffusion peak current in the absence of **1**.

TABLE 2. Coulometric Data and Product Distributions for Catalytic Reduction of 2 mM 1 by [Ni(tmc)]$^+$ Electrogenerated at Reticulated Vitreous Carbon Cathodes in DMF Containing 0.10 M TEABF$_4$

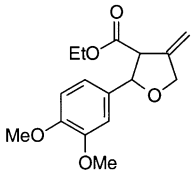
entry	[Ni(tmc)]$^{2+}$, mM	[HFIP], mM[b]	n[c]	product distribution, %[a] **2**	**3**	total
1	1		1.0	74	30	104
2	0.4		1.0	81	24	105
3	0.2		0.9	72	22	94
4	0.4[d]		0.9	85	<1	86
5	0.4	4	1.0	13	67	80
6	0.4	20	0.9	14	79	93
7	0.4	40	1.0	15	85	100
8	0.4[d]	40	0.9	<1	100	101

[a] % = yield expressed as the percentage of **1** incorporated into each product. [b] HFIP = 1,1,1,3,3,3-hexafluoro-2-propanol. [c] Number of electrons per molecule of **1**. [d] Carried out in DMF containing 0.10 M TBABF$_4$.

Controlled-Potential Catalytic Reduction of Ethyl 2-Bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (1). Table 2 lists coulometric data and product distributions obtained from a series of electrolyses in which [Ni(tmc)]$^+$ was electrogenerated from [Ni(tmc)]$^{2+}$ at a reticulated vitreous carbon cathode in the presence of various concentrations of **1** in DMF containing either 0.10 M TEABF$_4$ or TBABF$_4$. For all experiments the potential was set at 100 mV more negative than the peak potential for reduction of [Ni(tmc)]$^{2+}$. Each entry represents the average of three individual experiments, and the coulometric n value refers to the number of electrons transferred to each molecule of **1**. Controlled-potential catalytic reductions of **1** proceed smoothly, and current−time curves exhibit the expected exponential decay. At the end of an electrolysis, all of the starting material is consumed.

Several conclusions can be reached on the basis of the results in Table 2. First, catalytic reduction of **1** is a one-electron process that leads to the formation of a radical intermediate; other mechanistic features associated with the catalytic process are discussed below. Second, gas chromatographic analysis of the electrolyzed solutions

reveals the presence of two major products, 2-(3′,4′-dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methylenetetrahydrofuran (**2**) and 2-(3′,4′-dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methyl-2,5-dihydrofuran (**3**).



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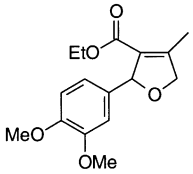

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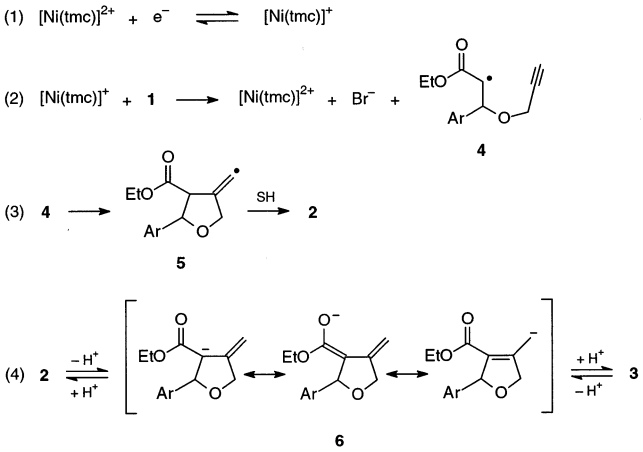
Although the sum of the yields of these two species is less than 100% in some experiments, we found no evidence (e.g., additional gas chromatographic peaks) for any other product. Third, the product distribution and the coulometric *n* value are not sensitive to changes in the initial concentration of $[Ni(tmc)]^{2+}$ (Table 2, entries 1−3).

In the absence of a deliberately added proton donor (Table 2, entries 1−3), the catalytic reduction of **1** in DMF containing 0.10 M $TEABF_4$ gives rise to **2** in approximately 76% yield and to **3** in approximately 25% yield. Performing catalytic reductions of **1** in DMF containing 0.10 M $TBABF_4$ (Table 2, entry 4) has no significant effect on the *n* value or the yield of **2**, although **3** is obtained in trace amounts. To probe the effect of an added proton donor, we electrolyzed solutions of DMF containing 0.10 M $TEABF_4$, 2 mM **1**, 0.40 mM $[Ni(tmc)]Br_2$, and 1,1,1,3,-3,3-hexafluoro-2-propanol (HFIP). As shown by entries 5−7 of Table 2, increasing amounts of HFIP cause no change in the *n* value, but the product distribution is significantly altered (**2** is obtained in yields of 13−15%, whereas **3** is formed in yields ranging from 67% to 85%). When the catalytic reduction of **1** is performed in DMF containing 0.10 M $TBABF_4$ and 40 mM HFIP (Table 2, entry 8), **3** is obtained almost quantitatively, whereas **2** is formed in trace amounts only. Thus, it is evident that the presence of a proton donor exerts a profound influence on the product distribution. In the following section, pertaining to mechanistic features of the formation of **2** and **3**, we deal with the effects of added HFIP as well as with the results of chemical experiments involving the isomerization of **2** to **3** in the presence of potassium *tert*-butoxide.

Mechanistic Aspects of the Catalytic Reduction of Ethyl 2-Bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)propanoate (1). On the basis of the coulometric *n* values and product distributions, we propose the mechanism shown in Scheme 1. After the reversible one-electron reduction of $[Ni(tmc)]^{2+}$ takes place (reaction 1), the resulting $[Ni(tmc)]^{+}$ transfers an electron to **1**, cleaving the carbon−bromine bond, to give radical intermediate **4**, as shown in reaction 2. According to detailed mechanistic studies by Bakac et al.[25−33] of the electroreduction of alkyl halides by $[Ni(tmc)]^{+}$ in aqueous media,

SCHEME 1



reaction 2 is likely to be the rate-determining step. Once produced, **4** undergoes rapid intramolecular cyclization to yield carbocyclic radical **5**, which, after abstraction of a hydrogen atom from DMF, affords **2** (reaction 3). There is substantial evidence in the literature that DMF can act as a hydrogen-atom donor.[34−37]

During electrolytic reductions in DMF, small amounts of electrogenerated bases accumulate.[38] Thus, in the absence of a proton donor (Table 2, entries 1−4), **2** can be deprotonated owing to the acidity of the proton adjacent to the carbonyl moiety, giving rise to the corresponding resonance-stabilized carbanion **6**. Then, as the rearranged carbanion is protonated, formation of **3** ensues (reaction 4). It is well-established in the literature[39] that unconjugated β,γ-unsaturated carbonyl compounds rearrange readily to their more thermodynamically stable conjugated isomers; for these base-catalyzed reactions, the intermediate is a conjugated dienolate ion, which is reprotonated at the γ carbon. In fact, Kimura et al.[40] have observed that electroreduction of allyl 2-chlorophenyl ethers gives rise to (*Z*)-enol ethers, probably as a result of isomerization induced by an efficient electrogenerated base. Isomerization of allyl ethers to (*Z*)-enol ethers has also been reported to be effected by a strong base such as potassium *tert*-butoxide.[41]

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Inasmuch as the aim of this work was to maximize the production of **2**, we were interested in examining the conversion of **2** to **3** under a variety of experimental conditions. Upon repeating an electrolysis of a 2 mM solution of **1** in the presence of 0.4 mM $[Ni(tmc)]Br_2$ in DMF containing 0.10 M $TEABF_4$, we obtained **2** in 70% yield and **3** in 24% yield, which is similar to the product distribution shown in entry 2 of Table 2. In this case, we attribute the appearance of **3** to isomerization promoted by electrogenerated base. However, when 40 mM HFIP was added to the catholyte *after* the electrolysis was concluded and the mixture was allowed to stand for approximately 6 h, the yield of **2** decreased to 36% and the yield of **3** increased to 61%. Conceivably, the increased degree of isomerization is due to the fact that the conjugate base of HFIP (which arises from its reaction with electrogenerated base) can deprotonate **2**, whereas HFIP itself can readily protonate **6**. In essence, the addition of HFIP to the electrolyzed solution creates a buffer that facilitates the isomerization. To probe further the isomerization process, we carried out a nonelectrochemical experiment in which a solution of DMF containing 0.10 M $TEABF_4$ and 2 mM **2** was treated with 0.25 equiv of potassium *tert*-butoxide. We analyzed this solution immediately by means of gas chromatography and found that 30% of the original **2** was converted into **3**. Then, we added 20 equiv of HFIP to this solution; after a reaction time of 5−6 h, the relative quantities of **2** and **3** became 49% and 51%, respectively. On the basis of results presented in Table 2, and in view of the latter experiments, we conclude that isomerization of **2** to **3** occurs under the conditions of an electrolysis and that the addition of HFIP enhances this conversion.

It is worthwhile to compare our findings with those obtained in several earlier investigations of the cyclization of halogenated ethers in the presence of either cobaloxime(III)[42,43] or nickel(II) complexes[44] as electron-transfer catalyst precursors. Torii et al.[42] have shown that cobaloxime(I) generated at a platinum cathode in methanol containing tetraethylammonium tosylate in a divided cell can promote the electroreductive radical cyclization of halogenated ethers to afford the corresponding tetrahydrofuran derivatives in 44−87% yield; it was concluded that the reaction proceeds through a closure in the exo mode to a five-membered ring only. Subsequently, an improved procedure was described for the electrochemical radical cyclization of brominated propargylic ethers, involving the use of chloro(pyridine) cobaloxime(III) and a sacrificial zinc anode in an undivided cell.[43] This approach is feasible with 5 mol % of the cobalt-containing catalyst and is applicable to a variety of brominated propargylic ethers under neutral conditions. In a later study, Ozaki et al.[44] examined the catalytic reduction of halogenated ethers under mild conditions by electrogenerated nickel(I) complexes, and it was discovered that various halides cyclize via the exo mode to a five-membered ring to give the corresponding tetrahydrofuran derivatives exclusively. In the same work, it was concluded that, since vinyl radicals are less stable than methyl radicals, the rates of hydrogen abstraction from a donor (possibly the solvent) by the former radicals are higher than those by the latter radicals, leading to higher yields of cyclized products. Indeed, similar behavior is evident when the yields of cyclic compounds obtained in the present work are compared with those reported in a recent publication[18] dealing with vinyl halides under comparable conditions.

In summary, we have demonstrated that the catalytic intramolecular radical cyclization of **1** by electrogenerated $[Ni(tmc)]^+$ to afford cyclic products can be accomplished and that the yield of the desired cyclic ester (**2**) is high enough to make this procedure an attractive alternative to other synthetic methods. Moreover, an advantage of this method is that the radical reactions can be carried out by use of a catalytic amount of an appropriate metal complex under mild experimental conditions at room temperature.

Experimental Section

Reagents. Each of the following chemicals was used as received: nickel(II) bromide, 1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane (tetramethylcyclam, tmc), 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP), potassium *tert*-butoxide, undecane, 1-ethylpiperidine hypophosphite, and AIBN. Dimethylformamide (DMF; "distilled-in-glass" reagent) was used as received. Tetramethylammonium tetrafluoroborate ($TMABF_4$), tetraethylammonium tetrafluoroborate ($TEABF_4$), and tetra-*n*-butylammonium tetrafluoroborate ($TBABF_4$) were stored in a vacuum oven at 80 °C to remove traces of water. Deaeration procedures were carried out with zero-grade argon. Published procedures were employed for the preparation of $[Ni(tmc)]Br_2$[45] and ethyl 2-bromo-3-(3′,4′-dimethoxyphenyl)-3-(propargyloxy)-propanoate (**1**).[6]

Synthesis of 2-(3′,4′-Dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methylenetetrahydrofuran (2) and 2-(3′,4′-Dimethoxyphenyl)-3-(ethoxycarbonyl)-4-methyl-2,5-dihydrofuran (3). A method based on that published by McCague et al.[10] was employed for the preparation of these two compounds. A stirred solution of **1** (0.500 g, 1.35 mmol), 1-ethylpiperidine hypophosphite (1.210 g, 6.38 mmol), and AIBN (0.044 g, 0.269 mmol) in toluene (50 mL) was heated at 80 °C for 4 h. Then, the resulting mixture was concentrated, and the residue was dissolved in dichloromethane. Next, the solution was filtered through a pad of Celite, and the filtrate was washed in succession with water and brine. After being dried over anhydrous magnesium sulfate, the organic phase was evaporated to afford a transparent greenish liquid that was largely a mixture of **2** and **3**. Flash column chromatography on a silica gel column with diethyl ether−petroleum ether as mobile phase gave two main fractions. We identified the first eluted material (40%), a yellow liquid, as **2** by means of ^1H NMR spectrometry (300 MHz) ($CDCl_3$): δ 1.28 (3H, t, J = 7.0 Hz), 3.49 (1H, apparent ddd, J = 8.7, 2.4, 2.4 Hz), 3.88 (3H, s), 3.90 (3H, s), 4.22 (2H, qABq, J = 7.0, 18.0 Hz), 4.50 (1H, apparent dq, J = 13.2, 2.4 Hz), 4.65 (1H, br apparent d, J = 13.2 Hz), 5.11 (1H, apparent q, J = 2.4 Hz), 5.19 (1H, d, J = 8.7 Hz), 5.20 (1H, apparent q, J = 2.4 Hz), 6.84 (1H, d, J = 8.7 Hz), 6.91−6.96 (2H, m). We identified the second eluted material (25%), another yellow liquid, as **3** by means of ^1H NMR spectrometry ($CDCl_3$): δ 1.15 (3H, t, J = 7.0 Hz), 2.19 (3H, d, J = 1.2 Hz), 3.87 (3H, s), 3.88 (3H, s), 4.08 (2H, qABq, J = 7.0, 11.0 Hz), 4.72 (1H, apparent ddd, J = 1.2, 3.6, 15.0 Hz), 4.89 (1H, apparent ddd, J = 0.9, 5.7, 15.0 Hz), 5.90 (1H, m), 6.83 (1H, d, J = 8.1 Hz), 6.84 (1H, br s), 6.88 (1H, dd, J =

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8.1, 1.8 Hz). We used these two compounds as standards for the determination of gas chromatographic response factors.

Electrodes. For cyclic voltammetry we fabricated a planar, circular working electrode with an area of 0.077 cm^2 by press-fitting a short length of 3-mm-diameter glassy carbon rod (Grade GC-20, Tokai Electrode Manufacturing Company, Tokyo, Japan) into a Teflon shroud. Working electrodes for controlled-potential electrolyses were disks (0.4 cm in thickness, 2.4 cm in diameter, and approximately 200 cm^2 in geometric area) sliced from reticulated vitreous carbon logs (RVC 2X1-100S, Energy Research and Generation, Oakland, CA). Procedures for the cleaning and handling of these electrodes have been described previously.[46]

All potentials are quoted with respect to a reference electrode consisting of a cadmium-saturated mercury amalgam in contact with DMF saturated with both cadmium chloride and sodium chloride;[47,48] this electrode has a potential of −0.76 V versus the aqueous saturated calomel electrode (SCE) at 25 °C.

Cells and Instrumentation. Cells for cyclic voltammetry[49] and for controlled-potential electrolysis[50] have been described in earlier publications. Cyclic voltammograms were obtained with the aid of a Princeton Applied Research Corporation (PARC) model 175 universal programmer coupled to a PARC model 173 potentiostat−galvanostat and were recorded with a Yokogawa model 3023 X−Y plotter. Controlled-potential electrolyses were carried out by means of the above-mentioned potentiostat−galvanostat equipped with a PARC model 176 current-to-voltage converter. Electrolyses were programmed and current−time curves were acquired, stored, and integrated by locally written software, which controlled a data acquisition board installed in a personal computer.

Identification and Quantitation of Products. Gas chromatographic analyses were accomplished with the aid of a Varian model 3700 dual-column instrument equipped with flame ionization detectors and coupled to a Hewlett-Packard model 3392A integrator. Products were separated with a 30 m × 0.32 mm i.d. capillary column (EC-5, Alltech Associates) with a stationary phase of poly(methylphenylsiloxane). A known quantity of an electroinactive internal standard (undecane) was added to a solution before each experiment to allow quantitation of the electrolysis products. Gas chromatographic response factors were measured experimentally with authentic samples of each product, and all product yields tabulated in this paper represent the absolute percentage of starting material incorporated into a particular species.

Identities of the electrolysis products were confirmed by means of a Hewlett-Packard 5890 Series II gas chromatograph coupled to a Hewlett-Packard 5971 mass-selective detector. For **2**: *m/z* (70 eV) 292, M^+ (23); 277, $[M - CH_3]^+$ (0.6); 218, $[M - CO_2C_2H_5 - H]^+$ (6); 165, $[(CH_3O)_2C_6H_3CO]^+$ (19); 126, $[H_5C_2O_2\text{-}CC_4H_5]^+$ (51); 98, $[C_5H_6O_2]^+$ (100). For **3**: *m/z* (70 eV) 292, M^+ (100); 277, $[M - CH_3]^+$ (16); 263, $[M - C_2H_5]^+$ (25); 215, $[M - C_2H_5O - CH_3OH]^+$ (49); 165, $[(CH_3O)_2C_6H_3CO]^+$ (66); 77, $[C_6H_5]^+$ (20); 29, $[COH]^+$ (44). These identifications were confirmed by a comparison of gas chromatographic retention times for the suspected products, under carefully controlled conditions, with those of the authentic compounds prepared above.

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