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Radical Ion Probes. 8. Direct and Indirect Electrochemistry of 5,7-Di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one and Derivatives

J. Paige Phillips, Jason G. Gillmore, Phillip Schwartz, Larry E. Brammer, Jr., Daniel J. Berger, and J. M. Tanko*

Contribution from the Department of Chemistry, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0212

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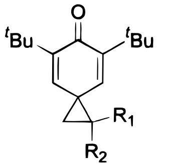
Abstract: Results pertaining to the direct and indirect electrochemistry of 5,7-di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (**1a**), 1-methyl-5,7-di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (**1b**), and 1,1,-dimethyl-5,7-di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (**1c**) are reported. Product analyses reveal that reduction of all these substrates leads to cyclopropane ring-opened products; ring opening occurs with modest selectivity leading to the more substituted (stable) distonic radical anion. The direct electrochemistry of these compounds is characterized by rate limiting electron transfer (with $\alpha \approx 0.5$), suggesting that while ring opening is extremely rapid, the radical anions *do* have a discrete lifetime (i.e., electron transfer and ring opening are not concerted). Utilizing homogeneous redox catalysis, rate constants for electron transfer between **1a**, **1b**, and **1c** and a series of aromatic radical anions were measured; reduction potentials and reorganization energies were derived from these rate constants by using Marcus theory.

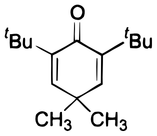
Introduction

In a preliminary report,[1] utilizing direct electrochemical techniques, we demonstrated that the radical anion generated from 1,1-dimethyl-5,7-di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (**1c**) undergoes rapid ring opening to yield (preferentially) the 3° distonic radical anion ($\mathbf{2c}^{\bullet-}$). Relief of cyclopropane ring strain and the generation of an aromatic ring provide the thermodynamic driving force for this rearrangement. Our interest in this system is related to the fact that **1c** has proven to be a highly effective "probe" for distinguishing between SET and conventional polar pathways in reactions of nucleophiles with carbonyl compounds based upon the observed regiochemistry of the products (Scheme 1). The observed behavior of this substrate in reactions with nucleophiles which do[2] and do not[3] react with carbonyl compounds via SET has confirmed the key elements of this hypothesis.

Because of the extremely high rate of ring opening associated with its radical anion, the direct electrochemistry of **1c** is characterized by rate limiting heterogeneous electron transfer. As a consequence, only rough estimates of the reduction potential of **1c** and the rate constant for ring opening of $\mathbf{1c}^{\bullet-}$ were obtained.[1] In this paper, further details pertaining to the direct electrochemistry of **1c** are provided. In addition, we report the electrochemical behavior of **1a**, **1b**, and model compound **2**, and apply homogeneous redox catalysis techniques to characterize the chemistry of this intriguing class of compounds.



1 (**a**: $R_1 = R_2 = H$)
(**b**: $R_1 = H$; $R_2 = CH_3$)
(**c**: $R_1 = R_2 = CH_3$)



2

Results

A. Direct Electrochemistry of 1(a→c) and 2. The cyclic voltammogram (CV) of **2** is characterized by a fully reversible, one-electron reduction wave from which $E^\circ_{2/2^{\bullet-}}$ could be determined directly ($E^\circ_{2/2^{\bullet-}} = -2.574$ V vs 0.1 M Ag^+/Ag). The CV's of **1a**, **1b**, and **1c** are all characterized by an irreversible reduction wave at approximately −2.4 V (vs 0.1 M Ag^+/Ag at 100 mV/s) and a reversible (or partly reversible) oxidation wave(s) at ca. −700 mV (Figure 1). Preparative scale (constant current) electrolysis of all three substrates leads to cyclopropane ring-opened products (Scheme 2; Note: Yields are based on consumed starting material).

These results are consistent with an EC-type mechanism as depicted in Scheme 3: **1** is reduced at the electrode surface to give radical anion $\mathbf{1}^{\bullet-}$. Ring opening of $\mathbf{1}^{\bullet-}$ yields distonic radical anions $\mathbf{3}^{\bullet-}$ and $\mathbf{4}^{\bullet-}$, which are either reduced further or undergo dimerization or disproportionation to yield, after acidic workup, the observed products. (The oxidation wave at −700 mV is assigned to the oxidation of the phenolate ions.)[4]

A thorough study by linear sweep voltammetry (LSV)[5] ensued. For all three compounds (a) the peak potential of the reduction wave (E_p) varied linearly with the log of the sweep rate, (b) E_p was *independent* of substrate concentration, and (c)

[⊗] Abstract published in *Advance ACS Abstracts*, December 15, 1997.

(1) Tanko, J. M.; Brammer, L. E., Jr.; Hervas', M.; Campos, K. *J. Chem. Soc., Perkin Trans. 2* **1994**, 1407.

(2) Tanko, J. M.; Brammer, L. E., Jr. *J. Chem. Soc., Chem. Commun.* **1994**, 1165.

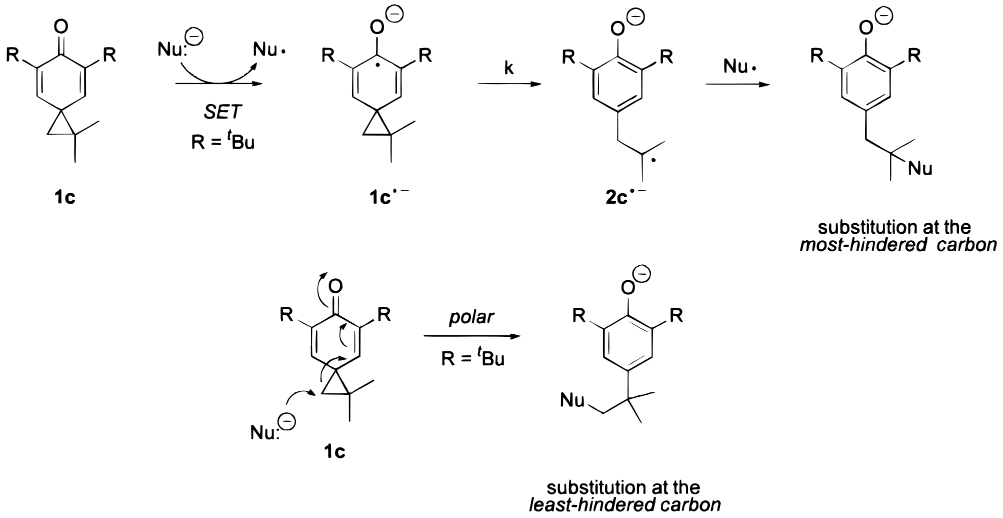
(3) Tanko, J. M.; Brammer, L. E., Jr. *J. Org. Chem.* **1997**, *62*, 5550.

(4) This assignment is supported by the following experiment: The cyclic voltammogram of the phenolate anion derived from 2,4,6-tri-*tert*-butylphenol (generated with potassium *tert*-butoxide in the presence of 18-crown-6) is characterized by a completely reversible oxidation wave with $E^\circ = -680$ mV vs 0.1 M Ag^+/Ag.

(5) Andrieux, C. P.; Savéant, J. M. In *Investigations of Rates and Mechanisms of Reactions, Part II*; Bernasconi, C., Ed.; Wiley: New York, 1986; pp 305−390.

S0002-7863(97)02795-9 CCC: $15.00

Scheme 1



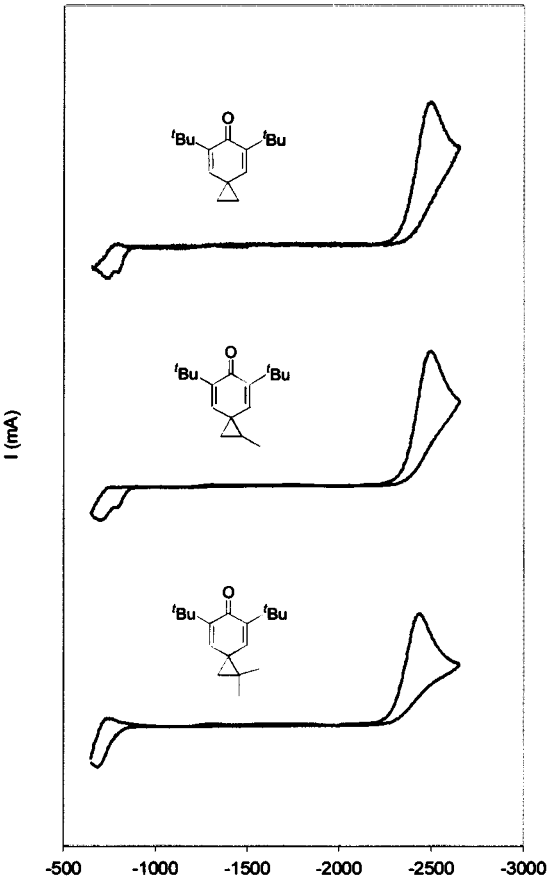


Figure 1. Cyclic voltammograms of **1a**, **1b**, and **1c** (0.5 M $^{n}Bu_4NClO_4$ in DMF, $\nu = 100$ mV/s, GCE, 0.003 M in substrate).

the peak width ($E_p - E_{p/2}$, the difference between the peak and half-peak potentials) was broad and did not vary as a function of sweep rate or concentration. Plots describing these experiments are provided in Supporting Information; results are summarized in Table 1.

Combined, the observed variation of E_p with sweep rate and the broadness of the reduction waves suggest that heterogeneous electron transfer is the rate-limiting step for the direct reduction of **1a**, **1b**, and **1c**. Transfer coefficients (α) were calculated from the slope of E_p vs log(ν) plot in accordance with eq 1,[5] and from the peak width according to eq 2.[5] Within experimental error, α values obtained via either procedure were identical (Table 1).

$$\alpha = \frac{RT}{2F}\frac{\partial \ln \nu}{\partial E_p} \tag{1}$$

$$\alpha = \frac{RT}{F}\frac{1.85}{E_{p/2} - E_p} \tag{2}$$

Because electron transfer is rate limiting, neither the reduction potential of these substrates nor the rate constant for ring opening of their radical anions could be determined by direct electrochemical techniques. However, these experiments help establish a lower limit for k_C. For an EC process, the competition between heterogeneous electron transfer (k_S) and a followup chemical step (k_C)[6] for kinetic control depends upon the parameter p (eq 3).[7] Making the assumption that for kinetic control by k_s, log

$$p = [\alpha nF\nu/RT]^{(\alpha-1)/2\alpha}[k_s^{1/\alpha}k_c^{1/2}]\,D^{-(1/2)\alpha} \tag{3}$$

$p \leq -1$,[7] and using (a) the median value for the transfer coefficient determined above ($\alpha = 0.54$) and (b) typical values for k_s and D (e.g., the literature values for benzoquinone determined under similar experimental conditions: $D = 1.2 \times 10^{-5}$ cm^2 s^{-1}; $k_s = 0.18$ cm s^{-1}),[8] we estimate that k_c is $\geq 10^6$ s^{-1} for ring opening of **1a**, **1b**, and **1c**. It should be noted, however, that this estimate of a lower limit for k_c depends heavily on the heterogeneous rate constant, k_s.

B. Indirect Electrochemistry of 1a, 1b, and 1c. Homogeneous redox catalysis[9] is a powerful technique for studying the chemistry of highly reactive intermediates produced via electron transfer. Consider the reactions depicted in Scheme 4. Rather than the substrate **A**, an electron-transfer mediator or catalyst **M** is reduced at the electrode surface. (In order for this condition to be met, the mediator must be more easily reduced than the substrate, i.e., $E°_{\mathbf{A/B}} < E°_{\mathbf{M/M^{\bullet-}}}$). Reduction of the substrate occurs via electron transfer from the reduced form of the mediator ($\mathbf{M}^{\bullet-}$).

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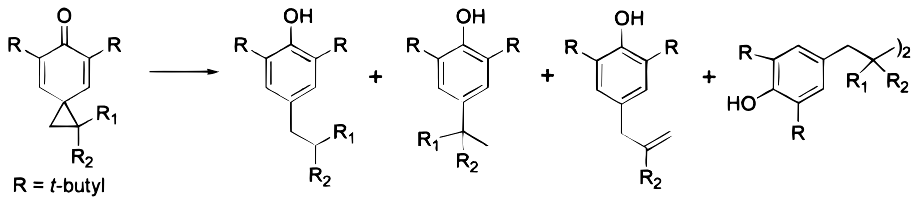
[6] For $\mathbf{1}^{\bullet-}$, $k_C = k_1$; for $2^{\bullet-}$, $k_C = k_1 + k_2$; for $\mathbf{3}^{\bullet-}$, $k_c = k_1 + k_3$.

[7] Nadjo, L.; Savéant, J. M. *Electroanal. Chem. Interfacial Electrochem.* **1973**, *48*, 113.

[8] Rosanske, T. W. Evans, D. H. *J. Electroanal. Chem.* **1976**, *72*, 277.

[9] (a) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savéant, J. M. *J. Electroanal. Chem.* **1980**, *113*, 12. (b) Savéant, J. M.; Su, K. B. *J. Electroanal. Chem.* **1985**, *196*, 1. (c) Andrieux, C. P.; Hapiot, P.; Savéant, J. M. *Chem. Rev.* **1990**, *90*, 723.

Scheme 2



1a ($R_1 = R_2 = H$)	48.4%			31.1%
1b ($R_1 = H$, $R_2 = CH_3$)	14.2%	31.6%	24.0%	
1c ($R_1 = R_2 = CH_3$)	31.7%	8.5%	51.3%	

Scheme 3

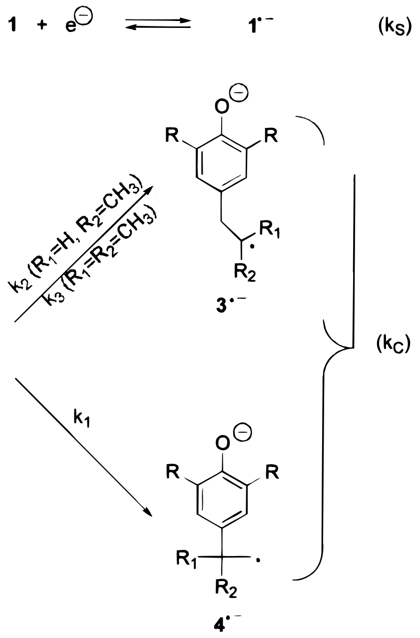


Table 1. LSV Analysis of **1a**, **1b**, and **1c**[a]

compd	$\partial E_p/\partial \log v$ (mV decade^{-1})	$\partial E_p/\partial \log C_A$[b] (mV decade^{-1})	$E_p - E_{p/2}$ (mV)	α[c]	α[d]
1a	51.8 ± 4.0	−0.3 ± 2.3	93 ± 5	0.57 ± 0.04	0.51 ± 0.04
1b	54.4 ± 4.0	−0.2 ± 2.5	93 ± 5	0.54 ± 0.04	0.51 ± 0.04
1c	48.5 ± 4.0	−0.9 ± 3.1	90 ± 5	0.61 ± 0.04	0.53 ± 0.04

[a] DMF solvent, 0.5 M ^{n}Bu$_4$NClO$_4$, $v = 100-1000$ mV/s. [b] $v = 100$ mV/s. [c] Calculated based upon $\partial E_p/\partial \log v$ and eq 1. [d] Calculated based upon ($E_p - E_{p/2}$) and eq 2.

Scheme 4

$$M + e^{\ominus} \rightleftharpoons M^{-\bullet}$$

$$M^{-\bullet} + A \underset{k_2}{\overset{k_1}{\rightleftharpoons}} M + B \qquad \text{ET step}$$

$$B \xrightarrow{k} C \qquad \text{Chemical step}$$

In this manner, the reference is taken away from the electrode and placed on the reversible 1e$^-$ reduction of a compound with a known $E°$. Effects of substrate addition on this reversible electron transfer are manifested experimentally by an increase in peak current and a loss of reversibility (if catalysis is occurring).

The key experimental observable is the current ratio i_p/i_{pd}, where i_p and i_{pd} are the voltammetric peak currents of the mediator in the presence and absence of the substrate, respectively, at a particular value of γ (the ratio of the substrate to mediator concentrations, $C°_A/C°_M$). Savéant *et al.* introduce the dimensionless rate constants λ_1, λ_2, and λ defined below (eqs 4→6, where ν is the sweep rate in V s^{-1} and *R*, *T*, and *F* have their usual meanings.)[9] Published working curves are available which depict the current ratio i_p/i_{pd} (a) as a function of log(λ_1) when the electron transfer step (k_1) is rate limiting or (b) as a function of log($\lambda\lambda_1/\lambda_2$) when the chemical step (*k*) is rate limiting.[9]

$$\lambda_1 = (k_1 C°_{\mathbf{M}}/\nu)(RT/F) \tag{4}$$

$$\lambda_2 = (k_2 C°_{\mathbf{M}}/\nu)(RT/F) \tag{5}$$

$$\lambda = (k/\nu)(RT/F) \tag{6}$$

As noted above, kinetic control may be goverened by either the homogeneous electron transfer step (k_1) or the chemical step (*k*, Scheme 4). If the rate of the chemical step is faster than back electron transfer ($k > k_2[\mathbf{M}]$), then the electron transfer step is rate limiting and k_1 can be determined experimentally. If the chemical step is slow relative to back electron transfer ($k > k_2[\mathbf{M}]$), the chemical step is rate limiting with the electron transfer step as a rapid pre-equilibrium. Under these conditions the composite rate constant kk_1/k_2 can be determined. (Because $\log(k_1/k_2) = 2.303F/RT(E°_{\mathbf{M/M}^{\bullet-}} - E°_{\mathbf{A/B}})$, *k* can be extracted if the reduction potential of the substrate is known.)

Though similar in appearance, different working curves pertain to these two conditions, and it is critical to accurately assess whether the kinetics are governed by the electron transfer or chemical step. For rate limiting electron transfer, the current ratio is a function of γ and λ_1, the latter of which is related to the mediator concentration (eq 4). For the rate limiting chemical step, i_p/i_{pd} is a function of γ and $\lambda\lambda_1/\lambda_2$, and is *concentration independent* at constant γ (eqs 4→6). Thus, the distinguishing characteristic between these two rate limiting conditions is the effect of mediator concentration ($C°_{\mathbf{M}}$) on i_p/i_{pd} at constant γ and ν. Peak current ratio varies as a function of mediator concentration only when the electron transfer step is rate limiting.

The reduction of **1a**, **1b**, and **1c** by several mediators was studied. Because of the limited quantity of these substrates available (they are not commercially available), it was more economical to examine the current ratio i_p/i_{pd} as a function of sweep rate and mediator concentration at constant excess factor γ (rather than by varying γ and keeping the sweep rate constant). As can be seen from eqs 7 and 8, at constant γ, i_p/i_{pd} is a function of log($C°_{\mathbf{M}}/\nu$) (when electron transfer is rate limiting) or log($1/\nu$) when the chemical step is rate limiting. Our approach was to obtain the voltammograms of several mediators in the

Table 2. Rate Constants for Homogeneous Electron Transfer between the Reduced Form of the Mediator and **1a**, **1b**, and **1c** (0.5 M ^{n}Bu$_4$NClO$_4$/DMF)

		k_1 (M^{-1} s^{-1})		
mediator	$E°$ (V)[a]	**1a**	**1b**	**1c**
fluoranthene	−2.150		2.8 (±0.2) × 10^2	8.4 (±0.5) × 10^2
4-cyanopyridine	−2.168	2.1 (±0.1) × 10^2	4.6 (±0.2) × 10^2	1.2 (±0.1) × 10^3
cyanonaphthalene	−2.246	5.6 (±0.3) × 10^3	7.9 (±0.5) × 10^3	2.0 (±0.2) × 10^4
9,10-diphenylanthracene	−2.250	7.2 (±0.5) × 10^3	9.7 (±0.6) × 10^3	2.8 (±0.2) × 10^4
9-phenylanthracene	−2.291	2.4 (±0.1) × 10^4	3.3 (±0.3) × 10^4	1.0 (±0.1) × 10^5
anthracene	−2.337	5.3 (±0.7) × 10^4	3.1 (±0.5) × 10^5	
9-methylanthracene	−2.359	2.4 (±0.3) × 10^5	3.5 (±0.6) × 10^5	

[a] Vs 0.1 M AgNO$_3$/Ag.

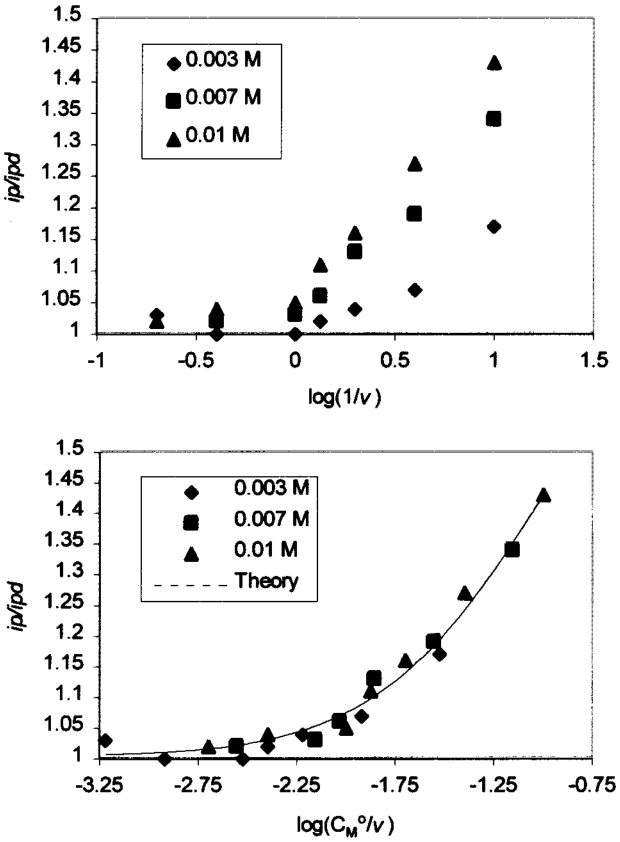


Figure 2. Mediated reduction of **1a** by 4-cyanopyridine (DMF, GCE, ^{n}Bu$_4$NClO$_4$, $\nu = 0.1{-}5$ V s^{-1}, $\gamma = 1.00$; dashed line is the working curve for rate-limiting ET, $x' = 0.722 \pm 0.017$).

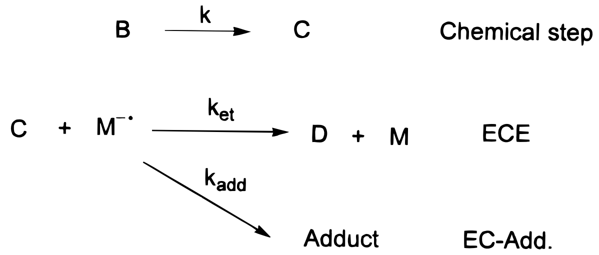
absence and presence of **1a**, **1b**, and **1c**. By comparing plots of [i_p/i_{pd} *vs* $\log(1/\nu)$] and [i_p/i_{pd} *vs* $\log(C°_M/\nu)$] obtained at different concentrations of mediator (γ constant), any concentration dependence is readily apparent. Representative plots are provided in Figure 2. For **1a**, **1b**, and **1c**, over the range of mediators examined, i_p/i_{pd} was found to vary as a function of mediator concentration (at constant γ). Thus for all these substrates, electron transfer was the rate limiting step, suggesting that the rate constant for the chemical step (ring opening) must be greater than 10^7 s^{-1}.

$$\log \lambda_1 = \log\left(\frac{k_1 RT}{F}\right) + \log\left(\frac{C°_M}{\nu}\right) \tag{7}$$

$$\log\left(\frac{\lambda\,\lambda_1}{\lambda_2}\right) = \log\left(\frac{k k_1 RT}{k_2 F}\right) + \log(1/\nu) \tag{8}$$

Kinetics of these systems were further complicated by a competing bimolecular reaction between $\mathbf{M}^{\bullet -}$ and the product of the chemical step (**C**, i.e., the ring-opened distonic radical anion) as described in Scheme 5. Coupling reactions between alkyl radicals and aromatic anion radicals are known to be fast and nearly diffusion controlled.[10] This competition between addition to the mediator (EC-add step) and the second electron reduction (ECE mechanism) must be considered in the overall reaction profile and introduces a new kinetic parameter ρ, where $\rho = k_{et}/(k_{add} + k_{et})$. The parameter ρ reflects the fraction of **C** that adds to the mediator. A treatment of this problem and the appropriate theoretical working curves have been published by Savéant.[11]

Scheme 5



Previously published working curves dealing with addition to the catalyst express i_p/i_{pd} as a function of γ.[11] In these experiments, i_p/i_{pd} was measured at various sweep rates at constant γ, and it was thus necessary to derive the appropriate working curves (21 plots of i_p/i_{pd} vs $\log(\lambda_1)$ at $\gamma = 1.00$ for $\rho = 0.00$ to 1.00 in 0.05 increments) via digital simulation.[12] These working curves were subsequently fit to a polynomial of the form $y = (a + cx + ex^2 + gx^3 + ix^4)/(1 + bx + dx^2 + fx^3 + hx^4 + jx^5)$, where the coefficients $a \rightarrow j$ were determined for each working curve.[13] Via nonlinear regression,[13] the experimental data [i_p/i_{pd} *vs* log ($C°_M/\nu$)] were fit to the polynomial form of the working curves, $y = f(x + x')$, and the adjustable parameter $x' = \log(k_1RT/F)$ was determined. The parameter ρ was determined by the working curve, which gave the best fit to the experimental data, and k_1 was determined from x'. A representative fit of the experimental data is provided in Figure 2, and the full treatment is provided in the Supporting Information. Table 2 summarizes the values of k_1 obtained for reduction

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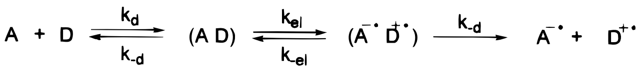
[10] For example, the rate constant for the coupling reaction between sodium naphthalene radical anion and the 1-hexenyl radical has been reported by Garst *et al.* to be 2 × 10^9 M^{-1} s^{-1} (Garst, J. F. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: Chichester 1972; Vol. 1, p 520); a value of 1 × 10^9 M^{-1} s^{-1} has been obtained by Pedersen and Lund in reactions between electrogenerated aromatic anion radicals and "radical clocks" in *N,N*-dimethylformamide.(Pedersen, S. U.; Lund, T. *Acta Chem. Scand.* **1991**, *45*, 397).

[11] Nadjo, L.; Savéant, J. M.; Su, K. B. *J. Electroanal. Chem.* **1985**, *196*, 23.

[12] DigiSim 2.1, Bioanalytical Systems Inc., 2701 Kent Avenue, W. Lafayette, IN 47906.

[13] TableCurve 2D, Jandel Scientific Software: 2591 Kerner Bvd., San Rafael, CA 94901.

Scheme 6



of **1a**, **1b**, and **1c** by a series of mediators. (For all mediators examined, $\rho = 0.00 \pm 0.025$.)

Discussion

A. Do 1a$^{\bullet-}$, 1b$^{\bullet-}$, and 1c$^{\bullet-}$ Exist as Discrete Intermediates? Previous studies dealing with rearrangements of radical anions derived from cyclopropyl ketones have identified two factors which influence the rate: (a) relief of cyclopropane ring strain (which provides the thermodynamic driving force favoring rearrangement) and (b) the difference in resonance energy associated with the ring-opened and ring-closed radical anions (which can help or hinder rearrangement, depending on the specific system).[14] Spiro[2.5]octa-4,7-dien-6-ones **1a**→**c** were selected for study because it was envisioned that ring opening of their corresponding radical anions would be especially facile because in addition to the relief of cyclopropane ring strain, ring opening generates an aromatic ring (i.e., the resonance energy of the product is *greater* than that of the reactant). Previously, using AM1 semiempirical MO theory, we estimated $\Delta H°$ for ring opening of **1c**$^{\bullet-}$ to be exothermic by 20 kcal/mol.[1] Given the large driving force for ring opening, it seems worthwhile to ask whether these radical anions actually have a discrete lifetime (i.e., does electron transfer and ring opening occur in a stepwise or concerted manner?)

The fact that the transfer coefficient (α) for **1a**, **1b**, and **1c** is nearly 0.5 is especially significant and suggests that the corresponding radical anions exist as discrete intermediates with a finite lifetime. Systems for which electron transfer and bond breaking are concerted (i.e., dissociative electron transfer) are typically characterized by α values significantly less than 0.5 (typically <0.4).[15]

B. Estimates of the Reduction Potential of 1a, 1b, and 1c by Using Marcus Theory. Several theories exist which relate the rate constant for electron transfer to the driving force, the preeminent of which is Marcus theory.[16] In the Marcus approach, **A** and **D** first diffuse together to form an encounter (or precursor) complex. After electron transfer, the products diffuse from the successor complex ($A^{\bullet-}$ $D^{\bullet-}$, Scheme 6).

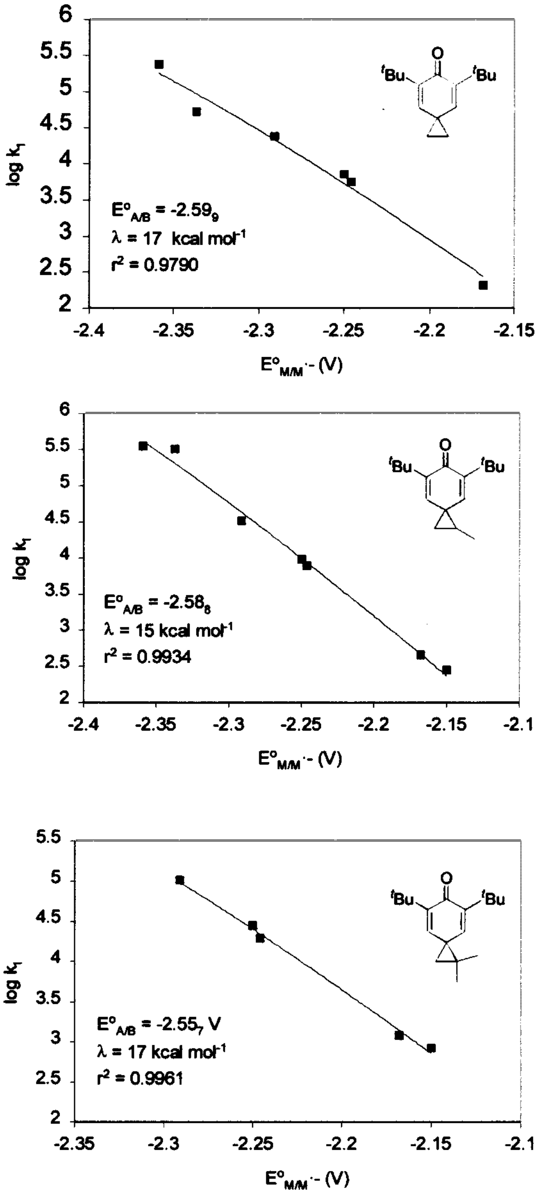


Figure 3. Rate constants for electron transfer from a series of mediators to **1a**, **1b**, and **1c** as a function of the reduction potential of the mediator ($E°_{A/B}$ and λ derived from the fit of data to eq 9, see text).

Equation 9 relates the rate constant for electron transfer (k_{obs}) to the free energy of the reaction ($\Delta G° = F(E_{\mathbf{M/M}^{\bullet-}} - E_{\mathbf{A/B}})$ and the reorganization energy (λ).[17,18] From left to right, the three terms in eq 9 represent different kinetic regimes: diffusion-controlled, activation-controlled, and equilibrium (or counter diffusion controlled), for which the slopes of the log(k_{obs}) vs $E_{\mathbf{M/M}^{\bullet-}}$ plots are zero, $-\alpha F/(2.303RT)$ (-8.5 V^{-1} for $\alpha = 0.5$), and $-F/(2.303RT)$ (-16.8 V^{-1}), respectively. In Figure 3, the log of rate constants for electron transfer (k_1) determined for the reactions of **1a**, **1b**, and **1c** with a series of mediators is plotted against the reduction potential of the mediator ($E°_{P/Q}$). For **1a**, **1b**, and **1c**, the slopes are -14.8, -15.5, and -15.2 V^{-1}, respectively, suggesting mixed kinetic control.

$$\frac{1}{k_{obs}} = \frac{1}{k_d} + \frac{1}{K_d Z \exp\left(\frac{-\lambda}{4RT}(1 + \Delta G°/\lambda)^2\right)} + \frac{1}{k_d \exp(\Delta G°/RT)} \tag{9}$$

Assuming $k_d = 1 \times 10^{10}$ M^{-1} s^{-1} (the diffusion-controlled rate constant in DMF), $K_d = 0.16$ M^{-1},[18] and the frequency factor $Z = 6 \times 10^{11}$ s^{-1}, the rate constants in Table 2 were fit to eq 9 via nonlinear regression analysis,[13] with $E°_{\mathbf{A/B}}$ and (λ as the only adjustable parameters. An excellent fit was achieved in all cases (the lines in Figure 3 represent the predicted values based upon this treatment), and $E°$'s and λ values were obtained (Table 3).

Derived values for the reorganization energy (λ) for **1a**, **1b**, and **1c** are reasonable considering the molecular functionality involved in these reactions (i.e., electron transfer from an aromatic hydrocarbon to a conjugated ketone), suggesting that there is not an additional contributor (such as bond lengthening

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[14] Tanko, J. M.; Drumright, R. E.; Suleman, N. K.; Brammer, L. E., Jr. *J. Am. Chem. Soc.* **1994**, *116*, 1785.

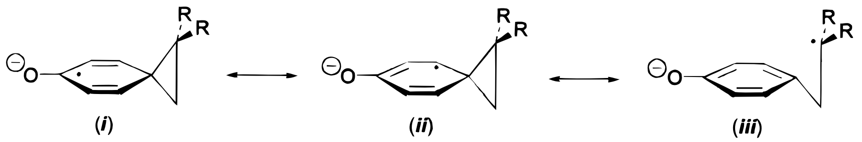
[15] Savéant, J. M. in *Advances in Electron Transfer Chemistry*; Mariano, P. S., Ed., JAI Press: Greenwich, CT, 1994; Vol. 4, pp 53−116.

[16] (a) Marcus, R. A. *J. Chem. Phys.* **1956**, *24*, 966. (b) Marcus, R. A. *Faraday Discuss. Chem. Soc.* **1960**, *29*, 21. (c) Marcus, R. A. *Annu. Rev. Phys. Chem.* **1964**, *15*, 155. (d) Marcus, R. A. *J. Chem. Phys.* **1965**, *43*, 679. (e) Marcus, R. A. *Faraday Discuss. Chem. Soc.* **1982**, *74*, 7. (f) For an excellent review see ref 18.

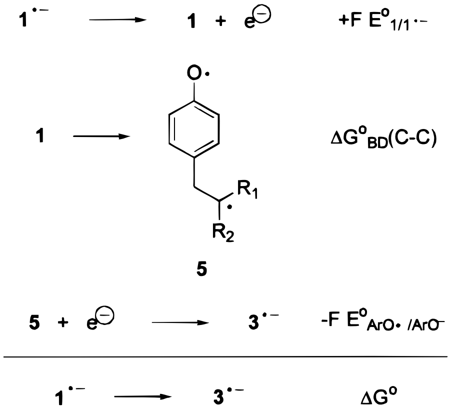
[17] Andrieux, C. P.; Savéant, J.-M. *J. Electroanal. Chem.* **1986**, *205*, 43.

[18] Eberson, L. *Electron Transfer Reactions in Organic Chemistry*; Springer-Verlag: Berlin, 1987; pp 25−34.

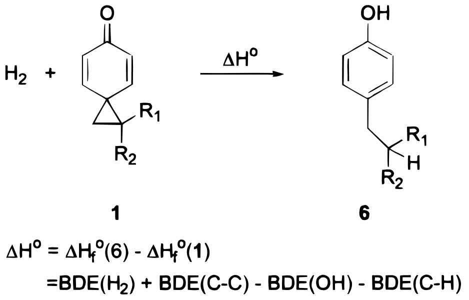
Scheme 7



Scheme 8



Scheme 9



Scheme 10

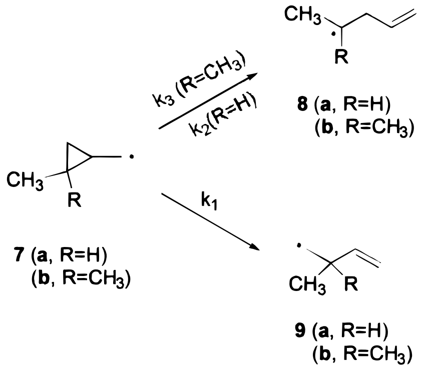


Table 3. Reduction Potentials and Reorganization Energies for **1a**, **1b**, and **1c**

compd	$E°$ (V)[a]	λ (kcal/mol)
1a	$-2.59_9 \pm 0.011$	17 ± 2
1b	$-2.58_8 \pm 0.005$	15 ± 1
1c	$-2.55_7 \pm 0.005$	17 ± 1
2	-2.574 ± 0.004	

[a] Vs 0.1 M Ag^+/Ag.

or bond angle changes) to the overall reorganization energy associated with these electron transfers. This provides an additional indication that ring opening occurs *after* electron transfer and these radical anions exist as discrete intermediates.

E° values derived from this analysis warrant further discussion. It is especially noteworthy that the derived *E*°'s for **1**(**a**→**c**) compare favorably to model compound **2**. This agreement suggests that the assumptions of this analysis are correct (*i.e.*, electron transfer is under mixed kinetic control), and thus provides additional evidence that electron transfer is stepwise, not concerted.

Table 4. Estimated Δ*G*° for Ring Opening of **1a**•−, **1b**•−, and **1c**•−

reaction	Δ*G*° (kcal/mol)
$1a^{\bullet-} \rightarrow 3a^{\bullet-}$	−11.2
$1b^{\bullet-} \rightarrow 3b^{\bullet-}$	−13.2
$1b^{\bullet-} \rightarrow 4b^{\bullet-}$	−10.0
$1c^{\bullet-} \rightarrow 3c^{\bullet-}$	−13.3
$1c^{\bullet-} \rightarrow 4c^{\bullet-}$	−5.3

Within experimental and statistical error, the *E*° values obtained for **1a**, **1b**, and **1c** are different. This same difference is also reflected in the individual rate constants obtained for any mediator (Table 2). With increased alkyl substitution on the cyclopropyl group, electron transfer becomes kinetically and thermodynamically more favorable. These observations can be nicely explained in light of the conjugative properties of the cyclopropyl group,[19] depicted by using resonance structures in Scheme 7, which stabilize the radical anion. Contribution of resonance form (iii) to the resonance hybrid is expected to be important because of its aromatic character,[20] and should be greater for $R = CH_3$ compared to R = H.

C. Thermodynamic Considerations. AM1 calculations suggest that ring opening of **1c**•− is exothermic by as much as 20 kcal/mol.[1] This estimate was based upon the difference in $\Delta H_f°$'s for the ring-opened and ring-closed forms of the radical anion, and of course refers to the gas phase. A vastly superior procedure for addressing the thermodynamics of ring opening is presented below. These calculations are based partly on experimental solution-phase measurements for the charged species and avoid the need to calculate any $\Delta H_f°$'s for odd-electron species with MO theory.

Δ*G*° for ring opening of **1a**•−, **1b**•−, and **1c**•− can be determined utilizing the thermochemical cycle depicted in Scheme 8 ($\Delta G° = \Delta G°_{BD}(C-C) + F(E°_{1/1^{\bullet-}} - E°_{ArO^\bullet/ArO^-})$. Three thermodynamic values are needed to solve for Δ*G*°: (1) the standard potential of the spiro[2.5]octa-4,7-dien-6-one ($E°_{A/B}$, Table 3), (2) the standard potential of the $ArO^\bullet/ArO^-$ couple (estimated to be −0.680 V based upon the cyclic voltammogram of the 2,4,6-tri-*tert*-butyl phenoxide anion),[4] and (3) the strength of the C−C bond of the cyclopropyl group ($\Delta G°_{BD}(C-C)$). It is assumed that Δ*S* for this unimolecular process is small and $\Delta G°_{BD}(C-C) \approx BDE_{C-C}$. This procedure for estimating Δ*G*° for ring opening is especially attractive because the pertinent reduction potentials used in this analysis were obtained in this laboratory and should adequately account for any effect of solvent and/or electrolyte.

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[20] Similar hyperconjugative interactions involving the out-of-plane C−H bonds in the cyclohexadienyl radical manifest themselves as an extraordinarily high a_H of 48 G in the EPR spectrum. Devolder, P.; Goudmand, P. *C. R. Seances. Acad. Sci. Ser. A* **1975**, *280*, 1281.

Strength of the cyclopropyl C−C in **1a**, **1b**, and **1c** was estimated according to Scheme 9, where $\Delta H_f°$'s for the pertinent species were obtained using semiempirical molecular orbital theory (PM3, details are provided in the Supporting Information),[21] and literature values for the bond dissociation energies: BDE(PhO−H) = 90.4 kcal/mol,[22] BDE(1°C−H) = 100.0 kcal/mol, BDE(2°C−H) = 98.5 kcal/mol, and BDE(3°C−H) = 95.6 kcal/mol.[23] We assume that these calculated values for BDE-(C−C) are the same in the gas phase and in solution.[24] Results of this analysis are summarized in Table 4.

D. Regiochemistry of Ring Opening. For unsymmetrical radical anions **1b**$^{\bullet-}$ and **1c**$^{\bullet-}$, ring opening occurs with modest selectivity, favoring the more-substituted (stable) distonic radical anion. On the basis of the yield of products observed in the preparative-scale electrolyses, $k_3/k_1 = 9.7$ (for **1c**$^{\bullet-}$) and $k_2/k_1 = 1.2$ (for **1b**$^{\bullet-}$). Consistent with the Hammond postulate, this low selectivity suggests an early (reactant-like) transition state for these ring openings, which is anticipated given their highly exothermic nature.

Notably, the selectivity observed for ring opening of these radical anions is remarkably similar to that observed for ring opening of the ring-substituted cyclopropylcarbinyl (neutral) free radicals. For example, ring opening of *trans*-**7a** leads to 2° and 1° radicals **8a** and **9a** in a 1.2:1 ratio (Scheme 10),[25] a value identical with that observed for **1b**$^{\bullet-}$. Dimethyl-substituted radical **7b** leads to 3° and 1° radicals **8b** and **9b** in a 6.7:1 ratio (Scheme 10),[25] vs 9.7:1 observed for **1c**$^{\bullet-}$. Ring opening of neutral radicals **7a** and **7b** occurs with rate constants greater than 10^8 s^{-1}. We anticipate that the rate constants for ring opening of **1b**$^{\bullet-}$ and **1c**$^{\bullet-}$ are of the same order of magnitude.

Summary

Radical anions derived from **1a**, **1b**, and **1c** undergo facile ring opening, with rate constants $\geq 10^7$ s^{-1}. Based upon the values of α observed in the direct electrochemistry of these compounds, the reorganization energy (λ) derived from the mediated reductions, and the fact that the derived $E°$'s closely match model compound **2**, we conclude that these radical anions have a finite lifetime (i.e., electron transfer and ring opening are not concerted). For unsymmetrical radical anions **1b**$^{\bullet-}$ and **1c**$^{\bullet-}$, ring opening yields preferentially the more substituted (stabilized) distonic radical anion. These results also provide evidence for stabilization of these radical anions via conjugative interactions with the cyclopropyl group, decreasing in the order **1c**$^{\bullet-}$ > **1b**$^{\bullet-}$ > **1a**$^{\bullet-}$. Both the rapid rate and selectivity associated with the ring opening of these radical anions can be exploited in the utilization of these substrates as "probes" for single electron transfer.

Experimental Section

General. Nuclear magnetic resonance spectra (^{1}H, ^{13}C, 2D NMR) were obtained on a WP 270 MHz Bruker, an AM 360 MHz Bruker, or a 400 MHz Varian Unity FT NMR spectrometer. All chemical shifts are reported in δ units relative to TMS (δ = 0.00 ppm) in $CDCl_3$. Infrared spectra were recorded on a Perkin-Elmer model 1600 FT-IR spectrometer. GC/MS was performed on a Fisons 8060 gas chromatograph with a VG Quattro mass spectrometer detector. High-resolution mass spectral data were obtained from a VG Analytical model 7070 E-HF double-focusing, magnetic sector, high resolution spectrometer using electron impact (70 eV) ionization. GC analysis was performed on a Hewlett Packard 5890A gas chromatograph equipped with an FID detector and an HP 3393A reporting integrator. High performance liquid chromatography (preparative and analytical scale) was performed with a Beckman System Gold 128 model solvent pump system with a 166 model UV/vis detector. Samples were separated with Beckman C-18 reverse phase columns (analytical: 4.6 mm × 250 mm; preparative: 21.2 mm × 150mm) with an 80/20 acetonitrile/water solvent system. Preparative thin layer chromatography separations (PTLC, Whatman, silica gel plates, 250 um layer, UV$_{254}$) were performed with hexane/ethylacetate solvent mixtures.

Electrochemical Measurements. The instrumentation and procedures employed for cyclic and linear sweep voltammetry and preparative electrolysis experiments have been previously described,[26] with the exception that in the direct electrochemical experiments the disk electrode surface was polished between each CV to minimize fouling between runs. Unless otherwise noted, typical measurements were performed on solutions containing 0.5 M n-Bu_4NClO_4 (TBAP) in dry *N*,*N*-dimethylformamide (DMF) at room temperature with use of a 5-mm-diameter glassy carbon electrode (GCE), a 0.1 M Ag^+/Ag reference electrode (+0.337 V vs SCE), and a Pt auxiliary electrode. A conventional H-cell, with the two compartments separated by a medium glass frit, was employed for preparative electrolysis experiments. The substrate was added to the cathodic compartment exclusively, and the cell was purged with dry, deoxygenated argon for several minutes prior to electrolysis. All preparative solutions contained 0.2 M TBAP and were electrolyzed at ambient temperature with a constant current of 30 mA, utilizing gold foil and coiled Cu wire as working and auxiliary electrodes, respectively. After electrolysis, the cathodic compartment was quenched with ca. 1 mL of 5% H_2SO_4, added to ca. 50 mL of water, and extracted with 4 × 50 mL of ether. Ether layers were combined, washed with water and saturated NaCl, dried over $MgSO_4$, and concentrated. Product isolations, characterizations, and quantitations were performed as noted.

Materials. *N*,*N*-Dimethylformamide (DMF, EM Science, 98%) was stirred over copper(II) sulfate (Aldrich, 98%) and activated alumina (Aldrich, neutral, Brockman activity I) for several days and vacuum distilled just prior to use. *Tetra*-*n*-butylammonium perchlorate (TBAP) was prepared by the method of House[27] and recrystallized 4× from ethyl acetate/hexane and vacuum oven dried before use. 5,7-Di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (**1a**),[28] 1-methyl-5,7-di-*tert*-butylspiro-[2.5]octa-4,7-dien-6-one (**1b**),[28] and 1,1-dimethyl-5,7-di-*tert*-butylspiro-[2.5]octa-4,7-dien-6-one (**1c**),[28] and 2,6-di-*tert*-4,4-dimethylcyclohexa-2,5-dien-1-one[29] were prepared through modification of previously published syntheses. 2,4,6-Tri-*tert*-butylphenol (Aldrich, 96%) was used as received. All catalysts used in this study except fluoranthene (Agros Organics, >98%) and anthracene (Matheson, Coleman & Bell, >98%) were obtained from Aldrich and used as received.

Electrolysis (Specific). Products of bulk electrolysis are all known compounds. Characterization was confirmed as needed (spectroscopic data available in Supporting Information), for compounds which were not commercially available.

5,7-Di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (1a). Electrolysis of 80 mg (0.34 mmol) of **1a** for 37 min at 30 mA (2 equiv of electrons) and subsequent workup and separation of crude oil via PTLC (1% EtOAC/hexane) yielded the following pure compounds: 2,6-di-*tert*-

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[21] For a series of representative cyclopropane derivatives, PM3 was found to accurately reproduce experimentally determined $\Delta H_f°$'s with an average error of ±4 kcal/mol. Details are provided in the Supporting Information.

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butyl-4-ethylphenol[30] (35 mg, 43%), 1,4-bis(3′,5′-di-*tert*-butyl-4′-hydroxybenzyl)butane[31] (22 mg, 28%), and unreacted starting material **1a** (10 mg, 11%) quantitated as 2,6-di-*tert*-butyl-4-(hydroxyethyl)-phenol[32] generated during the acidic workup.

1-Methyl-5,7-di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (1b). A 60 mg (0.24 mmol) sample of **1b** was electrolyzed for 20 min at 30 mA (1.4 equiv of electrons). After workup, the products were separated by preparative HPLC, using a 80/20 mixture of acetonitrile/water, characterized, and then quantitated on the HPLC, using the same solvent mixture: (2,6-di-*tert*-butyl-4-isopropylphenol[30] (16.5 mg, 27.7%), 4-allyl-2,6-di-*tert*-butyl-phenol[33] (12.5 mg, 21%), 2,6-di-*tert*-butyl-4-propylphenol[34] (7.34 mg, 12.4%), and unreacted starting material **1b**, quantitated as 2-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)propan-2-ol[35] (7.85 mg, 12.4%) formed as a result of the acidic workup.

1,1-Dimethyl-5,7-di-*tert*-butylspiro[2.5]octa-4,7-dien-6-one (1c). 1c (96 mg, 0.37 mmol) was electrolyzed for 43 min at 30 mA (2.2 equiv of electrons). After workup, the reaction mixture was analyzed by GC: 2,6-di-*tert*-butyl-4-isobutylphenol[36] (27.1%), 2,6-di-*tert*-butyl-4-(2-methylallyl)phenol[28] (43.9%), 2,4,6-tri-*tert*-butylphenol (7.3%), and 14.4% unreacted **1c**, quantitated as the two alcohols, 2-(3′,5′-di-*tert*-butyl-4′-hydroxybenzyl)-propan-2-ol[35] (11.8%) and 2-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)-2-methylpropanol[28,37] (2.6%), formed as a result of the acidic workup.

Acknowledgment. Financial support from the National Science Foundation (CHE-9412814) is acknowledged and appreciated. We also thank Ms. Beth Fletcher for help with the synthesis of **1a**.

Supporting Information Available: Plots pertaining to the direct and mediated reduction of **1a→c**, comparison of experimental and calculated (AM1, PM3) $\Delta H_f{}^\circ$'s of several cyclopropyl compounds, BDE(C−C) for **1a→c**, and tabulated spectral data for products formed by the electrolysis of **1a→c** (23 pages). See any current masthead page for ordering and Internet access instructions.

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