which involve more than one class of reaction. The reaction sequences presented in this section illustrate this facet of the program.

An isoquinoline synthesis utilizing three classes of reactions is shown in example S4.1.[83] The first step, treated by the electrophilic heterocyclic module, is addition of the amine to the benzaldehyde to form the Schiff's base. Reduction with sodium borohydride provides amine **28** as predicted by the oxidative/reductive module in CAMEO.[5,6] Upon resubmission of intermediate **28** to the heterocyclic module, the program finds the substitution reaction with ethyl bromoacetate to give **29**. Structure **29**, along with an acid catalyst, is then resubmitted to the heterocyclic module for further processing. Here, the program predicts that the most viable reaction is an electrophilic aromatic substitution; consequently, this reaction is transferred to the EAS module for evaluation. Intramolecular EAS finally provides the only predicted and reported[83] product.

Synthesis of a polycyclic indole system is illustrated in example S4.2.[84] Here, intermediate **30** is predicted by the electrophilic heterocyclic module as the initial product. Upon submission to the pericyclic module, **30** is then predicted to undergo a [3,3] sigmatropic rearrangement to give **31**. Subsequent analysis of **31** by the heterocyclic module provides the observed indole via intramolecular addition/deamination. Thus, in this manner, the program can arrive at the product of a Fischer indole synthesis.

V. Conclusion

The utility of the computer program CAMEO has been enhanced by the implementation of a package that treats reactions used in heterocycle synthesis. The heterocyclic package explicitly handles the major class of heterocycle-forming processes, i.e., electrophilic addition and substitution reaction under neutral and acidic conditions. The evaluation of these reactions required development of algorithms that consider nucleophile and electrophile reactivity, ring-size selectivity, and product formation. Regarding the last issue, a set of heterocyclic extended mechanistic steps was formulated for use in the construction of intermediates and products. Using a routine that assigns a mechanistic class to the input reactants, syntheses involving base-catalyzed and pericyclic reactions, electrophilic aromatic substitution, and radical or carbenoid intermediates can also be treated. Thus, the program is now capable of making predictions on the outcomes of a wide variety of heterocycle-forming processes.

Acknowledgment. Gratitude is expressed to the National Science Foundation for support of this work. M.G.B. also received fellowship support from Eastman Kodak, Inc.

---

(83) Teitel, S.; Brossi, A. *J. Heterocycl. Chem.* **1970**, *7*, 1401.

(84) Bahadur, G. A.; Bailey, A. S.; Baldry, P. A. *J. Chem. Soc., Perkin Trans. 1* **1977**, 1619.

Electroorganic Reactions. 31. Quinonemethide Radical–Anions and Dianions: Their Cathodic Generation and Reactivity

Marilia O. F. Goulart and James H. P. Utley*

Department of Chemistry, Queen Mary College, London E1 4NS, U.K.

Received August 31, 1987

The cathodic reactions of a number of relatively stable quinonemethides have been examined in detail by cyclic voltammetry, controlled potential coulometry, and rigorous product analysis following preparative-scale electrolyses. The results of cyclic voltammetric experiments differ in some respects from those of earlier polarographic work. The lifetimes of the electrogenerated radical–anions and dianions, in the absence of added electrophile, are governed by steric hindrance. Hindered intermediates are relatively long-lived yet hydrogenate in the presence of proton donor and alkylate in the presence of methyl iodide. Less hindered analogues efficiently and rapidly dimerize, at carbon, with concomitant protonation or O-methylation depending on added electrophile. The ambident cathodically generated nucleophiles alkylate at both carbon and oxygen, and the competition is crucially dependent on the cation (Bu_4N^+ or Li^+). Fuchsone **3** gives reduction products which vary with initial concentration and on the presence, or otherwise, of oxygen. Efficient reaction between oxygen and triarylmethyl radicals generated, e.g., from **3** has been demonstrated.

The electrochemistry of quinones received much early attention and provided some of the earliest examples of correlations between structure and redox potential. Despite this success, little attention has been paid to the electrochemical behavior of quinonemethides. The chemical reactions of quinonemethides are well understood and mostly involve the electrophilic character of the intermediates. Cathodic reduction brings about *umpolung*; the quinonemethides are converted into nucleophiles and bases, and we describe herein methods for the generation of such intermediates and preparative and electroanalytical experiments that illustrate their reactivity.

The quinonemethides chosen for study, compounds **1–6**, are relatively stable. Chemical reduction[1,2] and polarography[3] of compounds of this type have been investigated. There are also reports[4] of the preparative-scale electrolysis of quinonemethides, which indicate that hydrodimerization at the terminal carbon is a preferred reaction. Analysis of the polarographic results suggested[4b] that disproportionation of radical–anions might be significant. For less hindered and, consequently, more reactive quinone-

---

(1) Becker, H.-D.; Gustafsson, K. *J. Org. Chem.* **1976**, *41*, 214.

(2) Becker, H.-D.; Sanchez, D. *Tetrahedron Lett.* **1975**, 374.

(3) Krupicka, J.; Koutek, B.; Musil, L.; Pavlickova, L.; Soucek, M. *Collect. Czech. Chem. Commun.* **1981**, *46*, 861.

(4) (a) Richards, J. A.; Evans, D. H. *J. Electroanal. Chem. Interfacial Electrochem.* **1977**, *81*, 171. (b) Kudinova, L. I.; Volod'kin, A. A.; Ershov, V. V.; Prokofeva, T. I. *Izv. Akad. Nauk. SSSR, Ser. Khim.* **1978**, 1503.

0022-3263/88/1953-2520$01.50/0

Table I. Cyclic Voltammetric[a] and Coulometric[b] Experiments

entry	compd	$-E_{p,c}(1)$	$-E_{p,c}(2)$	$-E_{p,a}(1)$	$-E_{p,a}(2)$	n (concn, mM)	$-E_{red}$
1	**1**[c]	1.02	–	–	–	–	
2	**2**	0.85	–	(0.02)[d]	–	1.0 (5.1[e])	0.90
3	**3**	0.98	1.50	0.91 (0.02)		2.0 (0.6[e], 0.9[f])	1.70
						1.4 (2.8[f])	1.70
						1.4 (13[f])	1.70
4	**4**	0.22	0.49	0.15	0.43	1.8 (2.8[f])	0.70
		(0.32	0.46	0.23	–)[g]		
5	**5**	0.46	0.95	0.39	0.87		
		(0.37	0.78[h]	0.29	0.70)[g]		
6	**6**	0.39	0.91	0.32	0.85	ca. 2.0[i] (4.8[j])	0.60
		(0.48	0.92[h]	0.39	0.83)[g]		

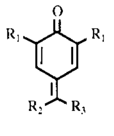
[a] Hg bead cathode, DMF/Bu_4NClO_4 (0.1 M), scan rate 0.5 V s^{-1}, reference electrode Ag/AgI(s). [b] Controlled potential electrolysis at E_{red} (vs Ag/AgI), in DMF/Bu_4NClO_4 (0.1 M), and at Pt foil or Hg pool as indicated; consumption of starting material monitored at intervals of charge by in situ cyclic voltammetric analysis. Linear plots of i_p vs Q extrapolated to $i_p = 0$. [c] CH_2Cl_2/Bu_4NI (0.1 M). [d] Irreversible reduction at $\nu < 16$ V s^{-1}; oxidation peaks at –0.02 V are probably due to product (see text and entry 3). [e] Pt cathode. [f] Hg cathode. [g] DMF/$LiClO_4$ (0.1 M). [h] Quasi-reversible, $i_{p,a}/i_{p,c} < 1.0$. [i] Nonlinear i_p vs Q plot; value from initial slope. [j] MeI added in excess.

Table II. Controlled Potential Electrolyses[a] without Added Electrophile

entry	compd	concn, mM	$-E_{red}$[b]	charge,[c] F mol^{-1}	conversion,[d] %	products (yield, %)[e]
1	**2**	10.9	1.00	0.9	77	**8**[f] (58), **9** (6), **10** (8)
2	**3**[g]	6.8	1.20	1.3	86	**13** (11), **11** (85), benzophenone (trace)
3	**3**	5.4	1.70	1.0	89	**13** (77), **11** (14)
4	**3**[h]	15.0	1.20	3.5	99	**13** (79), **11** (19)
5	**3**	13.1	1.70	1.5	95	**13** (53), **11** (38)
6	**3**[i]	13.2	1.70	1.4	92	**13** (42), **11** (27), benzophenone (15)
7	**4**	2.8	0.70	1.8	37[j]	**25** (90)
8	**6**	5.0	1.30	1.7	93	**16** (16)
9	**5**	5.8	1.10	2.0	85	**17** (trace), **23** (11), **24** (6)

[a] Hg cathode, divided cell, DMF/Bu_4NClO_4 (0.1 M). [b] V vs Ag/AgI(s); entries 1, 2, 4 at first wave, entries 3, 5–9 at second wave. [c] Charge required to attain background current; however, in many cases starting material was recovered on workup. [d] Allowance for recovered starting material. [e] Isolated yield, based on converted starting material. [f] (±):meso = 0.5. [g] Reduction product in contact with air before aqueous workup. [h] DMF/$LiClO_4$ (0.1 M). [i] O_2 bubbled through cell after electrolysis. [j] Conversion initially almost quantitative (^1H NMR and CV), starting material regenerated on workup.

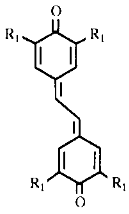
methides, attempted cathodic reduction initiates polymerization.[5] The considerable steric hindrance in compounds **2–6** inhibits such competing reaction; compound **1** is short-lived and was examined following in situ generation.



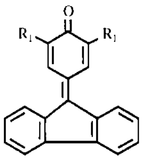
(1) R_1 = t-Bu R_2 = R_3 = H

(2) R_1 = t-Bu R_2 = H R_3 = Ph

(3) R_1 = t-Bu R_2 = R_3 = Ph



(4) R_1 = t-Bu



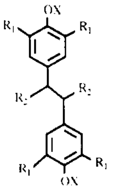
(5) R_1 = Me

(6) R_1 = t-Bu

Results and Discussion

Cyclic Voltammetric and Coulometric Experiments. Qualitative information on the reactivity of the cathodically generated intermediates was obtained by single-seep cyclic voltammetry, together with coulometric measurements and determinations of peak potentials (Table I). In each case, clean, diffusion-controlled behavior was observed as shown by linear plots of peak current versus (scan rate)$^{1/2}$ in the range 0.05–1.0 V s^{-1}. The irreversible reduction found for the least hindered compounds **1** and **2** is not surprising; the initially formed radical-anions are able rapidly to dimerize, the favored mode of cathodic reaction for activated alkenes. The cyclic voltammogram of **3** contains extra information.

A key feature of the voltammogram (see the paragraph at the end of the paper re supplementary material) is the anodic peak at E_p = –0.02 V, which is consequent upon sweeping past the second, irreversible peak at E_p = –1.50 V. The oxidation peak is probably due to an anion of the major product of reduction at low concentration, **13**. The simplest explanation is that it is the phenolate of **13** which

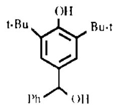


meso and (±)

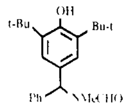
(7) X = H, R_1 = t-Bu, R_2 = Ph

(8) X = Me, R_1 = t-Bu, R_2 = Ph

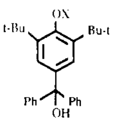
(27) X = H, R_1 = t-Bu, R_2 = H



(9)

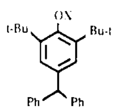


(10)



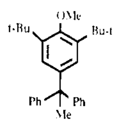
(11) X = H

(12) X = Me

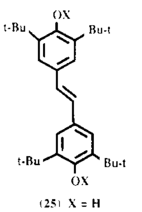


(13) X = H

(14) X = Me

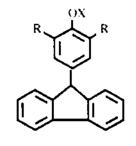


(15)



(25) X = H

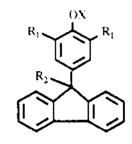
(26) X = Me



(16) X = H R = t-Bu

(17) X = H R = Me

(18) X = Me R = Me



(19) X = H R_1 = t-Bu R_2 = Me

(20) X = H R_1 = R_2 = Me

(21) X = Me R_1 = t-Bu R_2 = Me

(22) X = Me R_1 = R_2 = Me

(23) X = H R_1 = Me R_2 = OH

(24) X = H R_1 = Me R_2 = NMeCHO

---

(5) Chum, H. L.; Johnson, D. K.; Palasz, P. D.; Smith, C. Z.; Utley, J. H. P. *Macromolecules* 1987, *20*, 2698.

Table III. Controlled Potential Electrolyses[a] in the Presence of Methyl Iodide

entry	compd	concn, mM	$-E_{red}$[b]	charge,[c] F mol^{-1}	conversion,[d] %	products (yield, %)[e]
1	**1**	–	1.10	–	–	**27** (90)[f]
2	**2**	4.1	1.00	2.3	90	**8**[g] (80)
3	**3**	5.0	1.10	3.2	99	**14** (50), **15** (17), **13** (8), **11**, **12** (traces)
4	**3**[h]	5.5	1.73	ca. 1.2	74	**13** (10), **14** (33), **12** (50)
5	**3**[i]	5.0	1.70	ca. 2.0	91	**14** (24), **13** (54), **11** (3), **12** (trace)
6	**4**	1.6	0.70	3.8	98	**25** (91), **26** (8)
7	**5**	5.2	1.10	1.0	80	**22** (40), **18** (20), **20** (5), **17** (5)
8	**6**	5.9	1.20	1.4	80	**21** (39), **19** (32)
9	**6**	0.25	1.20	4.7	95	**21** (39), **16** (5)
10	**6**[j]	2.0	1.20	2.0	93	**21** (55), **19** (35), **16** (8)
11	**6**	4.8	0.60	3.8	86	**21** (45), **19** (36)
12	**6**[k]	0.23	(0.90–1.20)	4.9	88	**19** (67), **21** (17)

[a] Hg cathode, divided cell, DMF/Bu_4NClO_4 (0.1 M); MeI excess 5–15×. [b] V vs Ag/AgI(s); entries 1, 2, 3, 11 at first wave, entries 4–10, 12 at second wave. [c] Charge required to attain background current; however, in many cases starting material was recovered on workup. [d] Allowance for recovered starting material. [e] Isolated yield, based on converted starting material. [f] **1** generated in situ; crude yield, based on precursor. [g] (±):meso = 0.5. [h] MeI added after electrolysis and exposure to air. [i] MeI added immediately after electrolysis. [j] At Pt cathode. [k] DMF/$LiClO_4$ (0.1 M); V vs pseudo Ag wire reference.

gives on oxidation an intermediate (phenoxy radical?) sufficiently long-lived to be subsequently reduced at low potential; the potentials are similar to those measured from **13** by polarography.[6] The highly hindered quinonemethides **4**–**6** give reversible reduction at modest scan rates, which indicates the formation of relatively long-lived radical–anions and dianions. The peak separation, $E_{p,c}(2) - E_{p,c}(1)$, is smallest for compound **4**; presumably the linearity of the molecule allows maximum separation of charge in the dianion. The separation of peaks is further decreased in the presence of $LiClO_4$ (see below). In several respects the results from cyclic voltammetry (a non-steady-state technique) are in conflict with those from polarography[3] (a steady-state technique). The most important differences are that reduction of **2** gives one irreversible peak according to cyclic voltammetry but has previously[3] been described as giving two waves with the first reversible; similarly, reversibility of the second wave for **3** was implied, yet we observe irreversibility.

Cyclic voltammetric behavior may be modified by the addition of an electrophile (methyl iodide) or by changing the electrolyte cation from Bu_4N^+ to Li^+. In the presence of an excess of methyl iodide, the second reduction peaks for compounds **5** and **6** become irreversible with no significant change in peak current. Reduction of **4** is reversible at both waves except at scan rates <20 mV s^{-1}, when the second wave becomes quasi-reversible. In the presence of Li^+, the $E_{p,c}(2) - E_{p,c}(1)$ value for compound **4** is greatly reduced. The cathodic peaks are distinct but almost merged into one broad peak with a single reoxidation peak at $E_{p,a} = -0.23$ V. The products of the implied rapid reaction with added electrophile will be discussed further below. The cation effect has good literature precedent;[7] the anodic shifts in peak potential are probably a consequence of ion-pair stabilization of charge on the oxygen atoms. The quasi-reversibility at the second reduction potentials of **5** and **6**, observed in the presence of Li,$^+$ may be the result of some protonation by adventitious water carried in the solvation shell of the cation.

The coulometric experiments revealed a complete pattern of follow-up reactions (Table I). The *n* value for compound **3** is concentration dependent. At low concentration *n* approaches 2.0 whereas at relatively high concentration *n* drops to 1.4. This result, together with the detailed analysis of products, is particularly important in arriving at a mechanistic rationalization of the reductive behavior of quinonemethides.

Controlled Potential Electrolyses. Detailed product analyses were performed following cathodic reduction under a variety of conditions; results are summarized in Tables II and III. In the absence of added electrophiles (proton donors or methyl iodide), compounds **2** and **3** are cleanly reduced whereas **4**–**6** gives a complex mixture of products. The quinonemethide **1** was not reduced on a preparative scale in this study; its cathodic hydrodimerization has, however, been reported.[4a]

Controlled potential reduction of **2** gives products in agreement with those expected from the coulometric experiments (Table I, entry 2); the major product is the hydrodimer **7**, consistent with the value of *n* = 1.

Protonation can occur either through adventitious water in the solvent (DMF) or upon aqueous workup. This is not the case, however, for the reduction of the more hindered quinonemethide **3**, where the electrochemical behavior is concentration dependent. At low concentration, and at the second reduction potential, this compound is reduced to the hydrogenated product **13** although only 1 F mol^{-1} is consumed (Table II, entry 3). In this case it is likely that one of the added hydrogen atoms comes from H-atom abstraction rather than by a second electron transfer with subsequent protonation.

At higher concentration, reduction at both the first and second reduction potentials (Table II, entries 2, 5, 6) gave, *after exposure to air*, an increased amount of triarylcarbinol **11**.

The solution immediately following reduction is green, but introduction of air causes a rapid change to light yellow, and compound **11** is isolated. Also, the carbinol **12** was obtained in highest yield when the reaction mixture was exposed longest to air before workup (Table III, entries 3 vs 4). This result is comparable with that in Table II, entry 2. In one experiment, oxygen was bubbled through the electrolyte at the conclusion of electrolysis (Table II, entry 6). Benzophenone and traces of the 2,6-di-*tert*-butyl-1,4-benzoquinone were produced. This is consistent with the intermediacy of a hydroperoxide which decomposes eventually to quinone and benzophenone (cf. Scheme I). This is analogous to the well-known conversion of cumene into phenol and acetone.

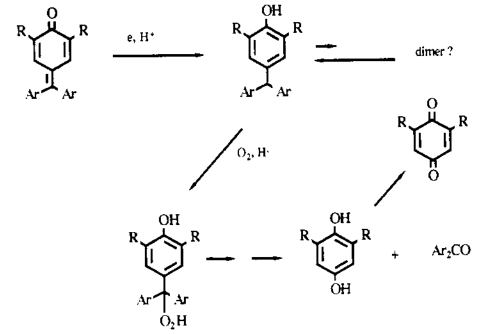
In a control experiment, the electrolyte, containing a trace of water, was preelectrolyzed at −1.7 V to replicate the alkaline conditions produced at the cathode. Subsequent addition of fuchsone **3** gave, after 3 h under nitrogen, no sign of reaction, and starting material was quantitatively

---

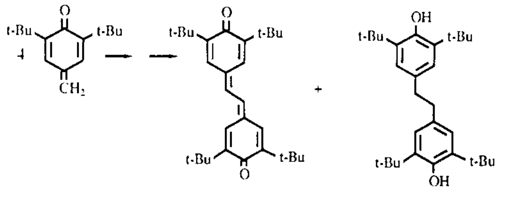
(6) Ioffe, N. T.; Prokof'ev, A. I.; Solodovnikov, S. P.; Volod'kin, A. A.; Nikiforov, G. A.; Ershov, U. V. *Izv. Akad. Nauk. SSSR, Ser. Kim.* **1971**, 2844.

(7) Mehta, R. R.; Pardini, V. L.; Utley, J. H. P. *J. Chem. Soc., Perkin Trans. 1* **1982**, 2921.

Scheme I



Scheme II



recovered. It is unlikely therefore that the carbinol **11** was formed by nucleophilic addition of hydroxide to the starting quinonemethide.

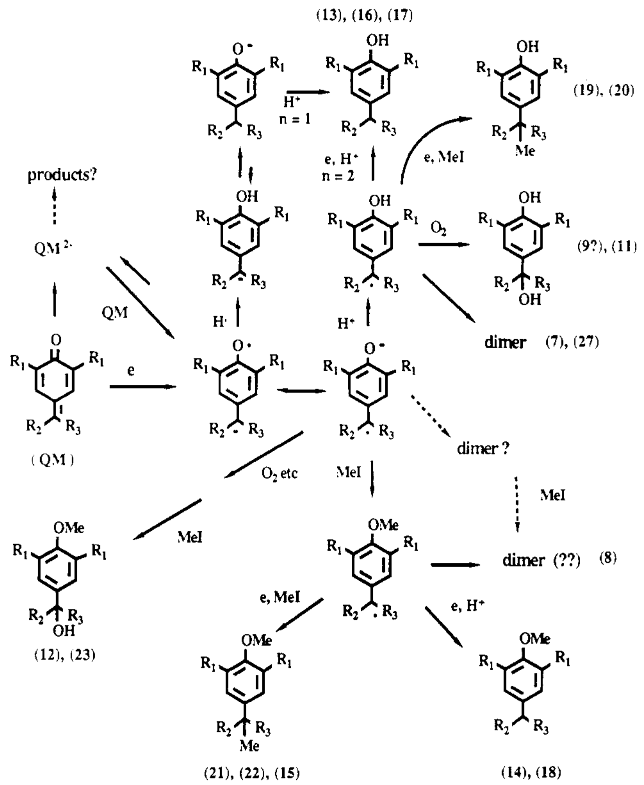
The results from the electrochemical reductions hint at the formation of a triarylmethyl radical which may react with oxygen, possibly according to Scheme I. The extent to which this may be dimerized in solution, prior to oxygenation and workup, has not been established. However, it is known[8] that the analogous dimer from triphenylmethyl radical reacts with oxygen at the exocyclic double bond and subsequent cleavage gives benzophenone and 4-(triphenylmethyl)phenol, i.e., a substitution pattern different from that observed by us. We suggest therefore that in our case it is the free radical that reacts with oxygen, not the dimer.

The quinonemethide **4** is converted by reduction into the stilbene derivative **25** although the isolated yield was apparently low (Table II, entry 7) and much starting material was recovered after workup, in air.

Cleaner electrolyses followed from the trapping of the anionic intermediates with methyl iodide (Table III). The least hindered and most reactive quinonemethide (**1**) gives (entry 1), according to TLC and ^{1}H NMR spectroscopic analysis, the bibenzyl **27** as the main product. Here there is a contrast with chemical behavior. It is known[9] that at high concentration compound **1** undergoes spontaneous dimerization combined with disproportionation (Scheme II). In the cathodic reaction, the bibenzyl **27** cannot be a product of reduction of **4** as a separate experiment (Table II, entry 7) shows this to be the stilbene derivative **25**. Measurement of the yield is in this case problematical because the quinonemethide must be generated in situ and in uncertain amount. However, it appears that all of the quinonemethide is converted into the dimer **27**. Presumably the considerable hindrance at the O atom precludes O-methylation; rapid coupling at the C atom is not hindered and could occur either directly between radical–anions or by Michael addition to starting material.

The alkylated dimer **8** is, however, produced efficiently from **2** (Table III, entry 2). The more hindered substrate **3** is, at the first potential, alkylated in a 1 F mol^{-1} process mainly at oxygen, but also (17%) at carbon. At the second potential, methyl iodide would itself be reduced. Consequently methyl iodide was added to the electrolyte after exhaustive (ca. 1.2 F mol^{-1}) electrolysis and after exposure to air. The products are exclusively those of O-alkylation, presumably because of initial oxygenation at C-7 (Table III, entry 4).

Scheme III



The stilbene derivative **25** is surprisingly the major product from reduction of **4** in the presence of methyl iodide (Table III, entry 6). The alkylated derivative, **26**, is produced but in much lower yield (entry 6). The overall conversion is high, and according to ^{1}H NMR spectroscopic analysis of the crude reaction product, the stilbene compounds are produced quantitatively. However, it was observed that solutions of **25** revert partly to starting material on standing in daylight.

Alkylation at both oxygen and carbon is the most significant feature of the reductive alkylation of **5**; the more hindered analogue, **6**, is clearly preferentially alkylated at carbon. For quinonemethide **6**, the supporting electrolyte cation profoundly affects the course of reaction (Table III, entry 12). A change from Bu_4N^+ to Li^+ almost suppresses O-alkylation, presumably by reducing the nucleophilicity of the oxygen anion by ion-paired interaction with Li^+. Similar cation effects on the reactivity of electrogenerated anions have been reported.[7]

Mechanistic Rationalization. The results described in Tables II and III, together with the results of voltammetric and coulometric experiments, may be accommodated in the sequence given in Scheme III. Some of the minor products, e.g., **9** and **10**, arise from chemical side reactions; we have not, for **9**, distinguished between formation by nucleophilic attack by adventitious hydroxide ion and reaction between oxygen and a quinonemethide-derived radical. The major products are given as arising via radical–anions although it is possible to device plausible routes involving dianionic intermediates. However, the equilibrium will lie heavily in favor of the radical–anions. For instance, the separation of the first and second reversible peak potentials for **4** is 0.27 V and for **5** and **6** is

---

[8] McBridge, J. M. *Tetrahedron* **1974**, *30*, 2009.
[9] Neureiter, N. P. *J. Org. Chem.* **1963**, *28*, 3486.

Table IV. Characterization of New Compounds

no.	experimental data
8	*meso*-, (±)-1,2-bis(3,5-di-*tert*-butyl-4-methoxyphenyl)-1,2-diphenylethane: mp 208–212 °C; IR ν_{max} (KBr) 3015, 2950, 1590, 1490, 1440, 1405, 1385, 1355, 1255, 1220, 1205, 1110, 1000, 880, 790, 770, 730, 690 cm^{-1}. Found: *m/z* 618.445. Calcd for $C_{44}H_{58}O_2$: 618.444. ^1H NMR spectroscopy (see supplementary material) indicates a mixture of meso (±) isomers.
10	(3,5-di-*tert*-butyl-4-hydroxyphenyl)phenyl(formylmethylamino)methane: mp 135–136 °C (petroleum ether, 40–60 °C); IR ν_{max} (KBr) 3450, 2945, 1650, 1415, 1395, 1225, 1145, 1110, 1070, 1045, 890, 770, 725, 695 cm^{-1}. Found: *m/z* 353.236. Calcd for $C_{23}H_{31}O_2N$: 353.235. Found: C, 78.36; H, 8.73; N, 3.82. Calcd for $C_{23}H_{31}O_2N$: C, 78.13; H, 8.84; N, 3.96.
12	(3,5-di-*tert*-butyl-4-methoxyphenyl)diphenylcarbinol: mp 131–133 °C (petroleum ether, 40–60 °C); IR ν_{max} (KBr) 3560, 3050, 2950, 1440, 1405, 1260, 1220, 1210, 1155, 1110, 1010, 890, 760, 740, 700 cm^{-1}. Found: *m/z* 402.256. Calcd for $C_{28}H_{34}O_2$: 402.256.
14	(3,5-di-*tert*-butyl-4-methoxyphenyl)diphenylmethane: mp 95–97 °C; ν_{max} (KBr) 3015, 1590, 1490, 1445, 1410, 1390, 1355, 1260, 1220, 1165, 1080, 1025, 1005, 890, 775, 750, 700 cm^{-1}. Found: *m/z* 386.263. Calcd for $C_{28}H_{34}O$: 386.261. Found: C, 86.72; H, 9.02. Calcd for $C_{28}H_{34}O$: C, 86.99; H, 8.87.
15	1-(3,5-di-*tert*-butyl-4-methoxyphenyl-1,1-diphenylethane: Found: *m/z* 400.271. Calcd for $C_{29}H_{36}O$: 400.277.
18	9-(3,5-dimethyl-4-methoxyphenyl)fluorene: mp 143–145 °C (MeOH); ν_{max} (KBr) 1590, 1440, 1410, 1260, 1220, 1110, 1000, 760, 730 cm^{-1}. Found: *m/z* 300.152. Calcd for $C_{22}H_{20}O$: 300.151. MS: *m/z* (relative intensity) 300 (42), 299 (33).
19	9-(3,5-di-*tert*-butyl-4-hydroxyphenyl)-9-methylfluorene: mp 125–127 °C; IR ν_{max} (KBr) 3620, 3060, 3000, 2950, 1440, 1430, 1365, 1355, 1310, 1255, 1235, 1210, 1155, 1115, 1105, 1090, 1020, 940, 930, 890, 880, 820, 805, 760, 750, 740, 730 cm^{-1}. Found: *m/z* 384.245. Calcd for $C_{28}H_{32}O$: 384.245. Found: C, 87.22; H, 8.24. Calcd for $C_{28}H_{32}O$: C, 87.44; H, 8.40. MS: *m/z* (relative intensity) 398 (100), 383 (38), 179 (40).
20	9-(3,5-dimethyl-4-hydroxyphenyl)-9-methylfuorene: mp 187–188 °C; IR ν_{max} (KBr) 3460, 3060, 1480, 1300, 1215, 1200, 1140, 1050, 760, 735, 730 cm^{-1}. Found: *m/z* 300.152. Calcd for $C_{22}H_{20}O$: 300.151. MS: *m/z* (relative intensity) 300 (49), 285 (100).
21	9-(3,5-di-*tert*-butyl-4-methoxyphenyl)-9-methylfluorene: mp 125 °C; IR ν_{max} (KBr) 1590, 1445, 1410, 1265, 1225, 1220, 1110, 1000, 760, 730 cm^{-1}. Found: *m/z* 398.262. Calcd for $C_{29}H_{34}O$: 398.261. MS: *m/z* (relative intensity) 398 (100), 383 (38), 179 (40).
22	9-(3,5-dimethyl-4-methoxyphenyl)-9-methylfluorene: mp 128–30 °C; IR ν_{max} (KBr) 1470, 1440, 1300, 1215, 1200, 1145, 1050, 760, 735, 730 cm^{-1}. Found: *m/z* 314.169. Calcd for $C_{23}H_{22}O$: 314.167. MS: *m/z* (relative intensity) 314 (73), 300 (56), 299 (100).
23	9-(3,5-dimethyl-4-hydroxyphenyl)-9-hydroxyfluorene. Found: *m/z* 302.132. Calcd for $C_{21}H_{19}O_2$: 302.131. MS: *m/z* (realtive intensity) 302 (100), 286 (33), 285 (61), 284 (72).
24	9-(3,5-dimethyl-4-hydroxyphenyl)-9-(formylmethylamino)fluorene: mp 238–240 °C; IR ν_{max} (film) 3450, 1660, 1230, 1055, 800, 750, 725, 695 cm^{-1}. Found: *m/z* 343.158. Calcd for $C_{23}H_{21}O_2N$: 343.157. MS: *m/z* (relative intensity) 343 (26), 286 (53), 285 (100), 84 (46), 59 (33).

about 0.5 V; the disproportionation constants, K_d, calculated from these values are 5.9×10^{-5} and 3.4×10^{-9} respectively.

No distinction is made in Scheme III between heterogeneous and homogeneous electron transfer. This mainly concerns the transfer of a second electron to radical intermediates. In the light of much recent mechanistic work, it is almost certain that these reactions follow DISP mechanisms[10] rather than ECE routes, i.e., the second electron transfer is homogeneous. For C-methylation it is also possible that electrocatalytic cleavage of the C–I bond is involved with subsequent combination of methyl radical and a quinonemethide-derived radical.[11] There is no precedent in electrochemical reactions for O-alkylation by radical coupling.

Experimental Section

Melting points are uncorrected. Mass spectra were obtained by using an A.E.I. MS-902 spectrometer in conjunction with an MSS Data Acquisition system. ^1H and ^{13}C NMR spectra were measured at either 80 MHz, 250 MHz, or 400 MHz on Bruker WP-80, AM-250, and WH-400 instruments respectively. NMR spectra were obtained by using $CDCl_3$ solvent with TMS reference unless otherwise stated.

Solvents and Electrolytes. ***N*,*N*-Dimethylformamide** (Aldrich, 99%) was purified by treatment with anhydrous copper sulfate (1 g/20 g of solvent) followed by careful fractional distillation at reduced pressure through a glass Vigreux column (40 cm) equipped with a nitrogen bleed. **Dichloromethane** was shaken with portions of concentrated sulfuric acid until the acid layer remained colorless. After aqueous washing and drying ($CaCl_2$), the solvent was distilled from phosphorus pentoxide and stored over molecular sieves (4A).

Tetra-*n*-butylammonium perchlorate (TBAP) was prepared by House's method[12] from the corresponding bromide and perchloric acid. The salt was recrystallized from ethyl acetate and dried carefully before use (2 days, in vacuo). **Lithium perchlorate** (Aldrich, anhydrous) was dried in vacuo for 48 h at 55 °C immediately before use.

Quinonemethides. Compounds **3–6** are known compounds, which were prepared by minor modifications of reported procedures. In each case the identity and purity of the material was confirmed by comparison of physical and spectroscopic data with that reported. In detail, fuchsone **3** was prepared by photochemical coupling and elimination starting[13] from benzophenone and 2,6-di-*tert*-butylphenol. 3,5,3′,5′-Tetra-*tert*-butylstilbene-4,4′-quinone (**4**) came from 2,6-di-*tert*-butyl-4-methylphenol[14] by lead dioxide oxidation. Condensation[1] of 9-bromofluorene with 2,6-dimethylphenol, followed by DDQ oxidation, gave 2,6-dimethyl-4-(9-fluorenylidene)-2,5-cyclohexadien-1-one (**5**). 2,6-Di-*tert*-butyl-4-(9-fluorenylidene)-2,5-cyclohexadien-1-one (**6**) was prepared by Wittig reaction between 9-fluorenylidenetriphenylphosphorane and 2,6-di-*tert*-butyl-1,4-benzoquinone.[1]

2,6-Di-*tert*-butyl-4-methylene-2,5-cyclohexadienone (1).[9] A solution of 3,5-di-*tert*-butyl-4-hydroxybenzaldehyde (1.12 g, 4.8 mmol) in aqueous sodium hydroxide (1 M, 20 cm^3)/methanol (5 cm^3) was treated with sodium borohydride (0.26 g, 6.8 mmol) at room temperature. Workup after 27 h with dilute sulfuric acid (1 N, 20 cm^3) and extraction with ether gave **4-hydroxy-3,5-di-*tert*-butylbenzyl alcohol**[15] as a white crystalline solid (0.53 g, 47%, mp 139–140 °C, lit. mp 138 °C). Trimethylsilyl chloride (0.3 cm^3) was added to a solution of the carbinol in dichloromethane (0.22 g, 0.93 mmol in 10 cm^3); the solution was shaken for 3 h and saturated aqueous sodium bicarbonate added (5 cm^3). After a further 10 min, the organic layer developed a light-yellow color. The dichloromethane layer was separated, dried ($MgSO_4$), and used immediately for cyclic voltammetric and controlled potential electrolysis experiments.

2,6-Di-*tert*-butyl-4-benzylidene-2,5-cyclohexadienone (2). Reaction in dry THF between 3,5-di-*tert*-butyl-4-hydroxybenzaldehyde (2.3 g, 10 mmol) and phenyllithium (2.5 cm^3 of 1.7 M solution in cyclohexane/ether) gave, after conventional workup and isolation by medium-pressure column chromatography, **(3,5-di-*tert*-butyl-4-hydroxyphenyl)phenylcarbinol**[15] (1.84 g, 59%, mp 220–221 °C, lit. mp 218 °). A portion of this carbinol (0.174 g, 0.56 mmol) was allowed to react with trimethylsilyl chloride as described for **1**. The solvent was removed from the

---

(10) Amatore, C.; Saveant, J. M. *J. Electroanal. Chem. Interfacial Electrochem.* **1977**, *85*, 27.

(11) Simonet, J.; Michel, M.-A.; Lund, H. *Acta Chem. Scand., Ser. B* **1975**, *29*, 489.

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

(13) Becker, H.-D. *J. Org. Chem.* **1967**, *32*, 2115.

(14) Cook, C. D. *J. Org. Chem.* **1953**, *18*, 261.

(15) Fitton, O. A.; Qutob, M. *J. Chem. Soc., Perkin Trans. 1* **1972**, 2660.

resulting yellow solution and the residue purified by medium-pressure chromatography to give the quinonemethide **2** as a yellow solid (0.13 g, 81%, mp 72–73 °C).[16] Suitable conditions for medium-pressure chromatographic purification involved the use of Fluka silica gel 60, eluted with petroleum ether (bp 40–60 °C)/dichloromethane (4:1 v/v).

Controlled Potential Electrolyses. Conventional glass cells were used with the anode and cathode compartments separated either by medium-porosity sintered glass or, better, by Celgard 2500 microporous polypropylene film. Solutions were degassed and an inert atmosphere was maintained in the cells by bubbling of dry nitrogen. Where DMF/TBAP was used, the electrolyte was preelectrolyzed at −1.7 V until the background current reached a low steady value (ca. 1 mA).

The following description is typical of the electrolysis procedures and methods for workup and isolation of products.

2,6-Di-*tert*-butyl-4-(diphenylmethylene)-2,5-cyclohexadien-1-one (3) (0.111 g, 0.3 mmol), dissolved in 55 mL of DMF/TBAP (0.1 M), was electrolyzed at an Hg pool cathode (7.0 cm^2) held at −1.70 V (Ag/AgI). A deep green color developed in the catholyte which decreased in intensity as reaction proceeded. Reaction was judged completed when the cell current had fallen to the background level (0.6 mA) after the passage of 1.02 F mol^{-1}. The light yellow catholyte was isolated, water added (25 mL), and the solution extracted with successive portions of ether. The combined extracts were washed (water) and dried ($MgSO_4$). Removal of solvent gave a yellow residue; medium-pressure chromatography (Fluka silica gel 60, petroleum ether (bp 60–80 °C)/dichloromethane (1:1) yielded **13** (0.077 g, 69%), recovered **3** (0.012 g, 0.033 mmol), and **11** (0.015 g, 13%).

The procedure was only slightly modified for electrolyses involving added methyl iodide. The methyl iodide could be added prior to electrolysis or following exhaustive electrolysis. As before, aqueous workup was followed by ether extraction and medium-pressure chromatography. In some cases it was advantageous to wash the ether extracts with saturated aqueous sodium chloride. Several difficult separations required repeated preparative-scale TLC. Plates used were coated (1 mm) with Merck silica gel 60 HF_{254}; for separation of **13** plus **14** from **3**, **11**, and **12**, CH_2Cl_2/Et_2O (1:1 v/v) was used with subsequently petroleum ether (bp 40–60 °C)/EtOAc (5%) to effect separations of **13** from **14**. The separation of **19** from **21** was also difficult; petroleum ether (bp 40–60 °C)/CH_2Cl_2 (95:5 v/v) proved to be a good solvent, yet three successive elutions were necessary.

A complete collection of ^1H NMR spectroscopic data of new compounds involved in this work is available (supplementary material). Table IV correspondingly lists physical, IR spectroscopic, mass spectrometric, and, where the amount of material was sufficient, microanalytical data. Where small amounts were obtained, the purity of samples was confirmed by TLC analysis in at least two solvent systems; in these cases, high-resolution mass spectrometry was used to confirm molecular formulas. For compounds **7** and **8**, the diastereoisomeric ratios were determined from the ^1H NMR spectra of the crude products; the benzylic protons are clearly resolved at high field. Benzylic proton signals for the meso isomers are upfield of those for the (±) isomers.[17]

Acknowledgment. We are grateful to the University of London Central Research Fund for an equipment grant and to the CNPq (Brazil) and the Federal University of Alagoas (Maceio, Brazil) for, respectively, a Fellowship and leave of absence to M.O.F.G.

Registry No. **1**, 2607-52-5; **2**, 7078-98-0; **3**, 13131-76-5; **4**, 809-73-4; **5**, 57196-35-7; **6**, 57196-25-5; **8**, 113894-03-4; **10**, 113894-04-5; **11**, 13145-53-4; **12**, 113894-05-6; **13**, 13145-54-5; **14**, 113894-06-7; **15**, 113924-39-3; **16**, 57196-50-6; **17**, 57196-34-6; **18**, 113894-07-8; **19**, 113894-08-9; **20**, 113894-09-0; **21**, 113894-10-3; **22**, 113894-11-4; **23**, 80826-88-6; **24**, 113894-12-5; **25**, 2950-01-8; **26**, 113894-13-6; **27**, 1516-94-5; DMF, 68-12-2; TBAP, 1923-70-2; CH_2Cl_2, 75-09-2; $LiClO_4$, 7791-03-9; CH_3I, 74-88-4; benzophenone, 119-61-9.

Supplementary Material Available: Cyclic voltammograms for fuchsone **3** in neutral and basic conditions; full ^1H NMR data for compounds **8**, **10**, **12**, **14**, **15**, **18**–**24** (3 pages). Ordering information is given on any current masthead page.

---

[16] Koutek, B.; Pavlickova, L.; Soucek, M. *Synth. Commun.* **1976**, *6*, 305.

[17] Schmid, G. H. *Can. J. Chem.* **1968**, *46*, 3415.

Oxidative [3 + 2] Cycloaddition of 1,3-Diketone and Olefin Using Electroorganic Chemistry

Jun-ichi Yoshida,* Kazuhiko Sakaguchi, and Sachihiko Isoe*

Institute of Organic Chemistry, Faculty of Science, Osaka City University, Sugimoto 3-3-138, Sumiyoshi, Osaka 558, Japan

Received August 14, 1987

The electrochemical oxidation of 1,3-diketones and 2-substituted 1,3-diketones in the presence of olefin gave the [3 + 2] cycloadducts, dihydrofuran and tetrahydrofuran derivatives, respectively. A mechanism involving electrooxidative formation of the radical intermediate from the diketone followed by addition to the olefin has been proposed.

Introduction

With increasing interest in synthetic application of radical reactions, a number of free radical mediated carbon–carbon bond-forming reactions have been reported recently.[1] The majority of such free radical reactions have been performed under reductive conditions. Oxidative radical reactions, however, seem to be advantageous from a synthetic point of view, because the radical is usually terminated by oxidation to the cation followed by the reaction with a nucleophile rather than by simple hydrogen abstraction. Although there have been reported several oxidative radical reactions mediated by metal salts such as Mn(III),[2,3] we have been interested in the generation

---

[1] (1) For example: (a) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon–Carbon Bonds*; Pegamon: Oxford, 1986. (b) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 753. (c) Hart, D. J. *Science (Washington, D.C.)* **1984**, *223*, 883.

[2] (2) For example: (a) Heiba, E. I.; Dessau, R. M. *J. Org. Chem.* **1974**, *39*, 3456. (b) Ito, N.; Nishino, H.; Kurosawa, K. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 3527. (c) Corey, E. J.; Kang, M.-C. *J. Am. Chem. Soc.* **1984**, *106*, 5384. (d) Snider, B. B.; Mohan, R.; Kates, S. A. *J. Org. Chem.* **1985**, *50*, 3661. (e) Fristad, W. E.; Peterson, J. R. *J. Org. Chem.* **1985**, *50*, 10. (f) Corey, E. J.; Ghosh, A. K. *Chem. Lett.* **1987**, 223 and references cited therein.

[3] (3) Oxidative radical C–C bond formation promoted by other metal salts such as cobalt has been reported. For example: (a) Bhandal, H.; Pattenden, G.; Russell, J. J. *Tetrahedron Lett.* **1986**, *27*, 2299. (b) Patel, V. F.; Pattenden, G.; Russell, J. J. *Tetrahedron Lett.* **1986**, *27*, 2303.

0022-3263/88/1953-2525$01.50/0